CANADIAN CLIMATE CENTRE

REPORT NO. 88-5

HELICOPTER AND AIRFRAME ICING POTENTIAL OFF THE CANADIAN EAST COAST

by

P. Roebber

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1988

THIS REPORT HAS RECEIVED ONLY LIMITED CIRCULATION BECAUSE OF THE SPECIAL NATURE OF THE PROJECT. HOWEVER, REFERENCE IS PERMITTED IF THE WORDS "UNPUBLISHED MANUSCRIPT" ARE MADE PART OF THE BIBLIOGRAPHIC ENTRY, IN ACCORDANCE WITH ACCEPTED PRACTICE.

OTHER CANADIAN CLIMATE CENTRE (CCC)
SCIENTIFIC SERIES INCLUDE:

1. CS series - CCC Climatological Study
2. CLI series - CCC Climatological Memoranda
3. CDS/DS series - CCC Climatic Data Summary
   - CCC Documentation Sheet

For further information on climatological publications contact the

Climatological Services Division
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4

HELICOPTER AND AIRFRAME ICING POTENTIAL OFF THE CANADIAN EAST COAST

Prepared for
Environment Canada
Atmospheric Environment Service

Under
Supply and Service Canada
Contract No. 0SC87-00235-(014)/A

by

P. Roebber

The MEP Company
7050 Woodbine Ave.
Suite 100
Markham, Ontario
L3R 4G8

A publication of the Canadian Climate Program

93-02177/

TABLE OF CONTENTS

		Page
ABSTRACT / RESUME		i
ACKNOWLEDGEMENT		ii
1. INTRODUCTION		1
2. PHYSICS OF THE ICING PROCESS		4
2.1	Airframe Icing	4
	2.1.1 Liquid Water Content	5
	2.1.2 Droplet-Object Interaction	10
	2.1.3 Runback and Runoff	14
	2.1.4 Thermodynamics	15
2.2	Helicopter Icing	16
3. CLIMATOLOGY OF AIRCRAFT ICING IN CANADA		21
3.1	Data Sources	21
3.2	Analysis	23
4. AIRCRAFT ICING MODELS AND FORECAST TECHNIQUES		36
4.1	Research Models	36
	4.1.1 Phase I: Generalized Ice Accretion Models	37
	4.1.2 Phase II: Airfoil Icing	40
	4.1.3 Phase III: Aerodynamic Performance Degradation	43
4.2	Diagnostic Models	48
5. CLIMATOLOGICAL AIRCRAFT ICING PREDICTION		68
5.1	Data Sources	68
5.2	Candidate Models	70
5.3	Model Implementation Strategy	77
6. CONCLUSIONS		99
REFERENCES		100

ABSTRACT

This report represents the first step in the development of a capability to estimate helicopter and airframe icing potential off the Canadian east coast with climatological data. The report contains a review of the physics of airframe and helicopter icing, documents the current level of knowledge concerning the extent of the aircraft icing hazard in Canada, provides a critical review of techniques for estimating airframe and helicopter icing potential, and outlines a strategy for implementing a number of candidate techniques in the MArine STatistics (MAST) climate information system.

RESUME

Ce rapport représente la première étape du développement de la capacité d'estimer, en utilisant les données climatologiques, le givrage d'aéronef et d'hélicoptères sur la côte est du Canada. Ce rapport contient une revue de la théorie physique du givrage d'aéronef et d'hélicoptères, et sert également à documenter l'importance du givrage pour l'aviation canadienne. Il contient aussi une critique des techniques disponibles pour estimer le danger du givrage d'aéronef, et il indique une stratégie pour la mise en oeuvre de quelques techniques dans le système d'informations climatologiques MAST.

ACKNOWLEDGEMENT

The MEP Company would like to express its appreciation of the efforts made by a number of individuals in contributing to the success of this project. In particular, the following people deserve special mention:

Mr. David Craig
Base Meteorological Officer,
CFB Shearwater, N.S.

Mr. Hans-Eberhard Hoffmann
DFVLR, Institute of Atmospheric Physics,
Oberpfaffenhofen, FRG

Dr. Edward Lozowski
University of Alberta,
Edmonton, Alberta

Mr. Les Welsh
Atmospheric Environment Service
Saskatoon, Sask.

Mr. Bogdan Jedrzejewski, Mr. Keith Davidson and Mr. Dan McGillivray of the MEP Company made contributions to the technical aspects of the project and Mrs. Connie Pirrotta typed the manuscript. Many thanks are also extended to Mr. Ross Brown of the Atmospheric Environment Service, the project's Scientific Authority, for his efforts and support.

Paul Roebber
The MEP Company

1. INTRODUCTION

Exploration and production of oil and gas along the Canadian east coast has been ongoing for a number of years. Helicopter support of offshore work is required both for transportation and emergency response; in addition, search and rescue operations require support from low-flying fixed wing aircraft. Such activity is highly weather dependent. In particular, atmospheric icing represents a serious hazard with potentially deleterious effects on helicopter flight capability (Korkan, Dadone and Shaw, 1984a,b; Flemming and Lednicer, 1986; Stallabrass and Price, 1967) and fixed wing aircraft performance (Toliver, 1987; Cooper et al., 1984; Dietenberger, 1984).

The frequency of occurrence of freezing precipitation and its impact on cancellation of helicopter flights to offshore rigs, has been investigated (Mitten et al., 1985). However, more detailed information concerning the spatial (horizontal and vertical) and temporal variations in aircraft icing potential for both freezing precipitation and in-cloud icing is needed to properly assess the climatological hazard to aircraft in the Canadian east coast region.

The satisfaction of this requirement will involve the development and implementation of a technique for assessing icing potential based upon standard archives of environmental data available for the Canadian east coast. This technique would be incorporated into the Marine Statistics (MAST) Suite of climate information systems to supplement the existing statistics on marine icing potential.

This project has addressed some of these requirements (Figure 1-1). In particular, the following objectives were met:

- the physics of helicopter and airframe icing were reviewed;

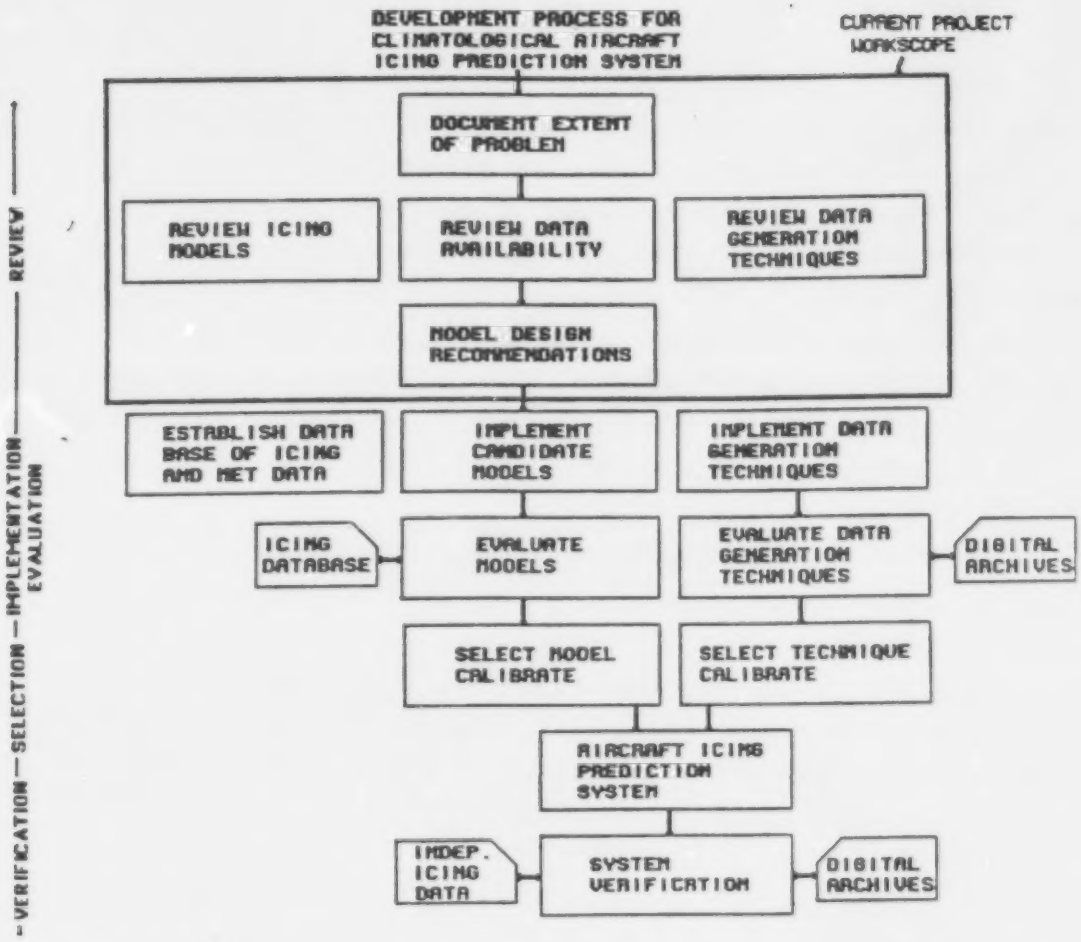


Figure 1-1: Conceptualization of the development process for a climatological ice accretion prediction system for aircraft.

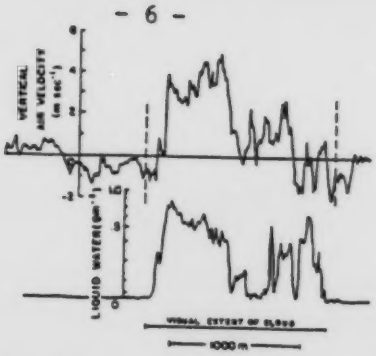
- the current level of knowledge concerning the extent of the aircraft icing hazard in Canada was documented;
- existing techniques for deriving estimates of airframe and helicopter icing potential were reviewed;
- a detailed model implementation strategy was presented.

2.1.1 Liquid Water Content

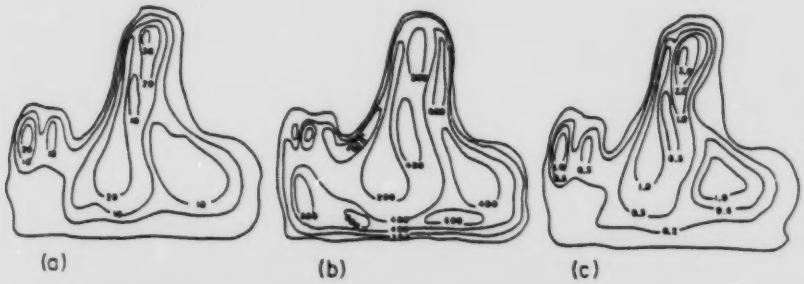
Sources of atmospheric liquid water that contribute to the aircraft icing process include cloud liquid water, freezing precipitation, supercooled fog and wet snow. The distribution of liquid water content within a cloud is a function of cloud type, cloud development (maturity) and cloud origin (e.g. maritime versus continental). In addition, cloud liquid water content (LWC) varies as a function of position within the cloud in the following way (Figure 2-1):

- LWC varies considerably over short distances at a given level in a manner closely related to the variation of vertical air velocity (Warner, 1969);
- LWC increases with height above cloud base, reaches a maximum in the upper half of the cloud and decreases towards cloud top (Warner, 1955; Mei-Yuan Huan, 1963);
- LWC distribution parallels drop size distribution rather than drop concentration (Mei-Yuan Huan, 1963);
- LWC is generally less than the adiabatic LWC, the ratio diminishing with height above cloud base and increasing with cloud width, reflecting the impact of the entrainment of dry air (Warner, 1955; Ackerman, 1959; Ackerman, 1963; Skatski, 1965, Warner, 1970).

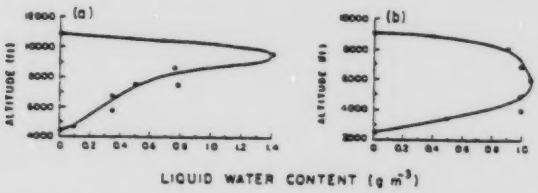
The presence and amount of supercooled droplets within a cloud is controlled by ice crystals which are favored to grow at the expense of the available moisture supply. Supercooled droplets are common and stable at temperatures down to about -15°C; below this level, large droplets freeze and ice crystals rapidly deplete available moisture. Gayet et al., (1984) showed that in both dry and wet growth regimes, ice accretion rates were diminished in the presence of ice crystals.



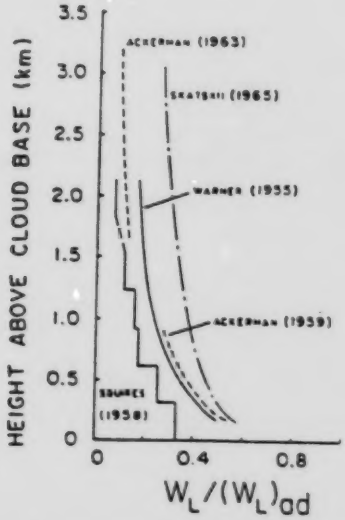
Vertical air velocity and liquid water content as function of distance from place of entering cloud. From Warner, 1969a



Spatial distribution of microstructure parameters in cumulus cloud. (a) drop diameter (μm), (b) drop concentration (number cm^{-3}), (c) w_L ($g\,m^{-3}$). From Mei-Yuan, 1963



Examples (a, b) for the variation of peak water content with height in cumulus clouds. From Warner, 1955



Ratio of the observed mean liquid water content at a given height above cloud base to the adiabatic value, for presumably non-precipitating clouds. From Warner, 1970

Figure 2-1

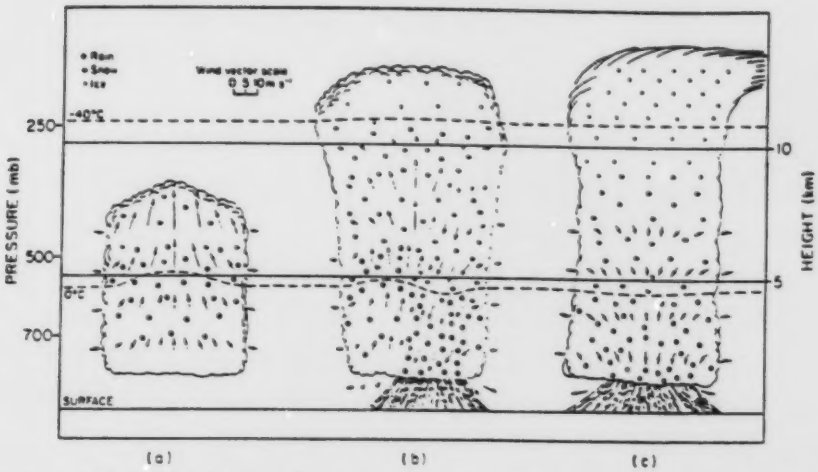
Warmer temperatures allow a greater moisture content in the air; the moistness of the air maximizes condensation and limits the loss of droplets by evaporation through the entrainment of drier air at the cloud boundaries. Lifting of the air, either through mechanical overturning by wind shear, convective ascent or large-scale vertical motion supports more abundant and larger water droplets; unstable air allows vertical motions to be sustained.

Well developed cumuliform cloud exhibits the instability and strong vertical velocity favourable to the growth and sustenance of large supercooled droplets. The stage of convective development is critical: in the case of a towering cumulus transforming to cumulonimbus (Figure 2-2), ice crystals multiply at the expense of supercooled droplets and as the thunderstorm dissipates, the icing zone is reduced to a shallow layer near the freezing level.

Layer clouds are limited in vertical extent, and generally exhibit weak vertical motions. As a result, supercooled liquid water content is relatively low, except where vigorous mechanical lifting (as in frontal zones) supports the growth of cloud droplets. However, stratiform cloud can cover relatively large horizontal areas and may contain abundant moisture where the cloud is sustained by large-scale lifting of a moist airmass (e.g. ahead of a warm front).

High clouds (cirrus, cirrostratus, cirrocumulus) normally consist of ice crystals; the presence of supercooled water droplets is rare.

Open bodies of water have the potential to increase icing in the cold season by maximizing vertical fluxes of heat and moisture to the overlying air (Ashley, 1945; Perkins et al., 1957; Voskresenskii and Chukanin, 1959).



Schematic description of a typical cell of an air-mass thunderstorm in three stages of its life cycle showing (a) cumulus stage, (b) mature stage, and (c) dissipating stage, based upon results of the Thunderstorm Project. The horizontal scale is compressed by about 30% relative to the vertical scale in the figure. (Adapted from "The Thunderstorm," U.S. Government Printing Office, 1949.)

Figure 2-2

Freezing rain and drizzle represent more advanced stages of cloud microphysical processes in the sense that cloud droplets have grown to sufficient size to precipitate out of the clouds. As a result, these processes present a serious problem to aviation since the potential exists for significant and rapid accumulation of ice. Freezing precipitation occurs when a shallow layer of subfreezing air exists beneath a warmer layer of air aloft through which droplets are falling. Freezing precipitation requires very specific meteorological conditions to occur:

- the warm layer must have sufficient depth to melt snow or ice particles from above;
- the cold layer must have sufficient thickness to produce supercooling of the drops yet not refreeze the particles.

In the Canadian east coast region, such conditions are unusual offshore, since sea surface temperatures in the region are generally above freezing even in mid-winter (Mortsch et al., 1985); this surface boundary condition promotes low level heating of cold air masses which tends to reduce the risk of subfreezing layers at low levels. Along the coast, however, freezing precipitation is fairly frequent since warm layers overlying cold surfaces are easily introduced by an onshore breeze off the open ocean in winter time. Mitten et al. (1985) showed that the occurrence of freezing precipitation comprised a very small percentage of total reports in the Grand Banks region, reaching a maximum of less than 2% in February. However, helicopter flight cancellations for freezing precipitation at and/or between St. John's airport and offshore rigs approached a maximum of 5% of all flight days in February and March (Mitten et al., 1985). Thus, while freezing precipitation is a relatively infrequent and intermittent phenomenon offshore, it represents a serious hazard to aviation and has an impact on offshore operations.

Supercooled fog and wet snow represent sources of ground-based icing. Supercooled evaporation fogs are an extremely rare phenomenon offshore (Mitten et al., 1985), with maximum frequencies of occurrence well below 1%. These fogs are formed when subfreezing air overlies a much warmer and more moist surface such as the open water. The cold air is unable to retain the moisture evaporating from the surface; this moisture condenses into the supercooled droplets that form the fog when the heat and moisture from the surface is mixed with the overlying cold and dry air. Since this process acts to quickly destroy the heat and moisture gradients necessary for its production, the phenomenon is isolated and short-lived. Wet snow accumulations may occur when snow is falling at temperatures very near 0°C such that a thin coating of liquid water is present which freezes on impact with a surface. Wet snow sticking to aircraft may freeze upon takeoff if an aircraft encounters much colder temperatures while climbing. Such conditions can occur frequently in coastal areas, since cold air masses moving offshore are heated from below, resulting in destabilization and moistening of the boundary layer, with relatively warm air at low levels and much colder air aloft. Little information exists concerning the impact of wet snow on aviation, although at least two crashes of commercial aircraft in the past few years have been associated with these conditions.

2.1.2 Droplet-Object Interaction

Assessment of droplet-object interaction requires the determination of the air stream flow and droplet trajectories around the accreting object. To calculate droplet trajectories, it is necessary to integrate the equation of motion for droplets in a flow field; commonly, the numerical solutions of Langmuir and Blodgett (1946) have been used to determine droplet motion. The principle of collection efficiency (the ratio of mass flow of impinging water droplets to the mass flow of droplets which would have struck the accreting object if not deflected by the air stream) is used to

simplify the computation. Recently, the theory of Langmuir and Blodgett was experimentally tested to determine its validity for computing water droplet collision efficiencies (Makkonen and Stallabrass, 1987). The results demonstrated that the basic theory of Langmuir and Blodgett was sound, but, the original tabulated data (which was obtained via analog computer) was somewhat inaccurate. Finstad et al. (1987) recently recalculated the collision efficiency data by integrating the droplet trajectories on a modern computer; the analytical expression for collection efficiency derived was found to provide a better fit to the experimental data of Makkonen and Stallabrass (1987). The new expression is:

$$E = A - 0.028 - C\,(B - 0.0454) \qquad (2\text{-}2)$$

where

$$A = 1.066K^{-0.00616} \exp\left(-1.103K^{-0.688}\right)$$
$$B = 3.641K^{-0.498} \exp\left(-1.497K^{-0.694}\right)$$
$$C = 0.00637\,\left(Re^2/K-100\right)^{0.381}$$

K is the non-dimensional inertia parameter (Stokes number) given by:

$$K = \rho_w V d^2/9\,\mu D$$

and Re is the droplet Reynolds number:

$$Re = \rho_a d V/\mu$$

where

d = droplet diameter
D = object (cylinder) diameter
ρ_w = density of water
μ = absolute viscosity of air
ρ_a = density of air
V = free stream velocity.

Collection efficiency is sensitive to droplet and target size. As a result, droplet size distributions need to be considered for accurate estimates of total collection efficiency. A simplification frequently employed is to compute collection efficiency based upon the median volume drop diameter. The error involved in this assumption was investigated by Makkonen (1984). He concluded that errors were negligible except for small values of collection efficiency, where errors in input date might be of greater significance than the median volume diameter assumption. However, these tests were conducted for relatively low free stream speeds of 10-30 m/s. Tests of total collection efficiency for a range of conditions more applicable to aircraft icing were made and are presented in Table 2-1. The results show that the maximum error involved in the assumption is on the order of .02 when inaccuracies in the input data are taken into account. Bragg and Gregorek (1982) also concluded that the selection of a median volume droplet diameter is a reasonable simplification at the higher speeds of aircraft.

The theoretical work of Hansman (1985) and the observations of Cooper et al. (1984) and Sand et al. (1984) suggest that relatively low liquid water content clouds can represent a significant aviation hazard if composed of a relatively few large droplets. In such situations, the median volume droplet diameter assumption results in reasonable estimates of total collection[1]. The above solutions are restricted to

---

[1] The median diameter droplet represents that diameter in a sample such that half the sample contains larger diameter droplets and half contains smaller droplets. The median volume diameter represents that diameter such that half of the water volume of the sample is contained in smaller droplets and half is contained in larger droplets. The distinction is important: computations based on cloud water droplets of the Khrgian-Mazan distribution show underestimates of total water collection on the order of 30 to 50% can results if the median diameter droplet size is used.

TABLE 2-1

Tests of Total Collection Compared to the Median Volume Diameter Collection Efficiency for a Range of Conditions

Distribution	T(°C)	V(m/s)	E(TOTAL)[1]	E(MEDIAN)[1]
1	-5±5	80±5	.118-.132	.094-.108
2	-5±1	80±5	.253-.272	.280-.300
3	-5±1	80±5	.364-.383	.361-.382

[1]Based on 3 inch cylinder diameter.

Diameter (m)	Distribution (drop size spectra)[2] 1	2	3
3	20	7	12
6	41	11	16
9	30	24	16
12	8	33	18
15	1	18	16
18	0	6	11
21	0	1	7
24	0	0	2
27	0	0	2
30	0	0	0

[2]Based on Bain and Gayet (1982).

the impact of droplets with a cylindrical object. The patterns produced by airflow around an object require complex potential flow computations relevant to the specific geometry of the target, including modifications to the geometry due to ice accretion. Such work has been carried out for an arbitrary airfoil by Lozowski and Oleskiw (1983); an extended version of that code was recently completed at the University of Alberta (Lozowski, 1987, personal communication). Additional work has been carried out by Bragg (1984, 1985).

2.1.3 Runback and Runoff

When the portion of the fluid that freezes upon impacting the target is less than 100%, a film of water covers the accreting surface. This film is subject to drag and gravitational forces which cause the unfrozen water to move away from the point of impact. Runback, unfrozen water that migrates across the accretion surface, can be significant at the high speeds of aircraft. Runoff, that portion of the unfrozen water that is lost due to splash, gravitational drop-off and surface blow-off, may also be important (Ackley and Templeton, 1979; Lozowski et al. 1979).

Liquid water resulting from runback and runoff comprises an additional source term in those regions of direct impingement. In the case of airframe icing, it is to be expected that runback will be the primary source term for those regions downwind of the leading surface edges. A simplified approach to the problem of runback, first proposed by Lozowski et al. (1979), is the following:

- all unfrozen water from each section, oriented in the direction of airflow, is assumed to flow into the next section in sequence as runback;
- in the final section, all unfrozen water is shed into the airstream as runoff.

2.1.4 Thermodynamics

Once the total mass flow of liquid water arriving at the accreting surface through direct impingement and runback is known, it is necessary to evaluate all heat source and sink terms to determine what portion of the water load can freeze (the freezing fractor, n). A heat balance approach is generally taken; that is, the sum of all heat source and sink terms is zero so that the surface maintains thermal equilibrium, and thermodynamic changes occur instantaneously so that heat transfer is always from the surface at the equilibrium temperature. The details of the heat balance terms have been provided in numerous other works (Roebber and Mitten, 1987; Brown and Roebber, 1985; Makkonen, 1984; Jessup, 1984) and will not be repeated here. However, it should be noted that two terms gain importance at the high speeds of aircraft. The first is the heating of air due to adiabatic compression and viscous work in the air boundary layer, which is proportional to the square of the flow speed. The second term is the heat loss from 'splash-off'. List (1977) showed that the net collection efficiency of a cylinder was strongly dependent on airspeed. The shed water, if at a lower temperature than the incoming droplets, will carry heat away from the collector and can have a significant impact on accretion rates. The heat balance equation is then solved for n, the freezing fraction, either directly or using numerical methods. The density of the accretion is related to the equilibrium freezing temperature, droplet radius and droplet impact velocity (e.g. Macklin, 1962), although empirical equations have not been developed for the higher speeds of aircraft.

Recently, Olsen and Walker (1986) presented experimental evidence suggesting that the current physical model of aircraft ice accretion may need to be modified. Using close-up movies and still photographs of the icing process at several positions along the surface of a small airfoil for a range of conditions, they found no flow of liquid over the ice surface after a short initial flow, even at

relatively warm temperatures. Rather, their work suggested that very large, stationary drops on the ice surface lost water from their bottoms by freezing and were replenished by the collection of cloud droplets. Under this condition, the current physical model involving the freezing fraction concept fails while the concept of rime ice accretion, when cloud droplets freeze almost immediately on impact, remains correct. The authors suggested that the freezing fraction needs to be replaced by a complex transient process involving the rapid increase in heat transfer for rough glaze ice. However, this work remains controversial, and further study is required before specific changes to modelling assumptions would be warranted.

2.2 Helicopter Icing

The primary distinguishing feature between the physics of airframe icing and helicopter icing relates to the different employment of their airfoils for flight. The high speed rotors utilized by helicopters requires the consideration of the following additional processes in the icing physics:

- distribution of tangential and radial airspeed along the span of the rotor;
- cyclic variation of airspeed in forward flight;
- cyclic pitch-changing of rotor blades;
- effects of centrifugal forces on runback and ice deposits;
- size scale of rotor blade versus wing;
- vibrational effects.

In addition, helicopters are generally restricted to lower altitudes and airspeeds than are usually attained by fixed-wing aircraft.

Because of the rotation of the blades, tangential airspeed is a function of the distance along the span from the rotor hub:

$$V_{tangential} = \omega r$$

where is the rotation rate of the blades and r is the distance along the span. Typically, tangential speeds can range from 0 at the hub to near Mach 1.0 at the blade tips. In addition, in forward flight, a cyclic variation of airspeed is introduced for a given point along the span, typically completing a full cycle in less than 0.2 seconds (Figure 2-3). As a result of forward flight, a cyclical radial flow is likewise introduced along the length of the span. The effect of these flows and their rapid variation must be taken into account in determing the droplet-blade interactions and subsequent flow of the liquid water film (Lozowski et al. 1979). Large centrifugal forces are also introduced which must be considered in assessing the runback flow and the adhesion of ice deposits. Accretion of ice on the rotors leads to contamination of the airfoil, seriously affecting the aerodynamic performance of the craft (Flemming and Lednicer, 1986). In addition, self-shedding of the ice build-up can cause uncontrollable balance problems, serious vibration, and generation of high-speed projectiles that can damage the helicopter. Itagaki (1984) used a balance of force analysis to estimate adhesive and tensile strengths of ice on rotor blades; based on that methodology, 1-3 cm of ice might accrete on the blades before shedding would occur. Those levels of icing might lead to reductions in lift-to-drag ratios of 50%, based upon the work of Flemming and Lednicer (1986); this reduction in performance occurs primarily as a result of increased blade drag, although small decreases in lift are also experienced. The result is increased engine power requirements to maintain the same rotor speed and lift forces. Numerous researchers have demonstrated the sensitivity of the aerodynamic performance of helicopters to the spanwise extent of icing, particularly in the blade tip region (Korkan et al., 1984a; Flemming and Lednicer, 1986; Lake and Bradley, 1976).

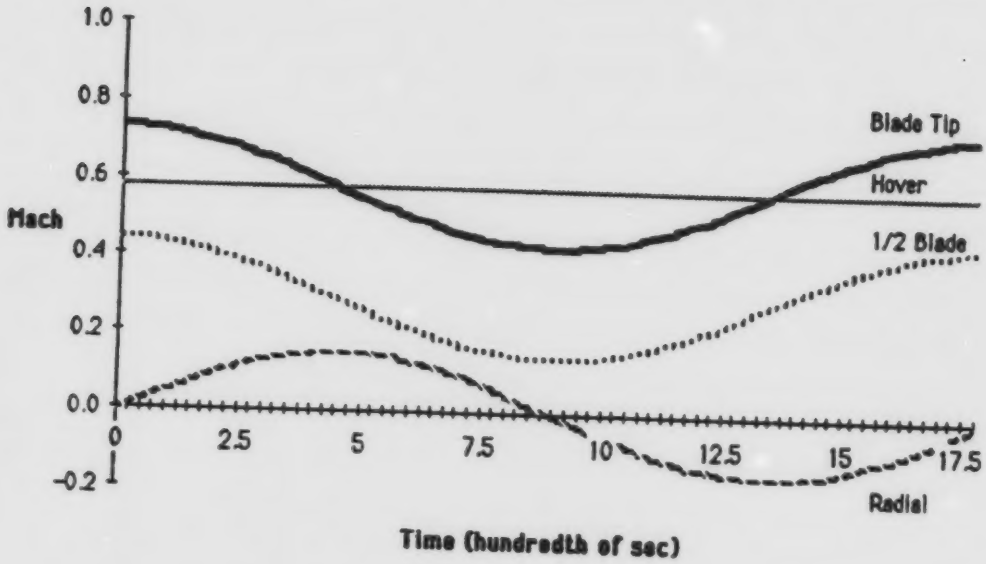


Figure 2-3: Variation in helicopter blade tangential speed as a function of span position and time. Based on a rotation rate of 344 rpm, blade length of 5.4 metres from hub to blade and a forward speed of 50 m/s.

The cyclic pitch-changing of the rotor blades must be taken into account in considering the collection of droplets and the performance of iced blades; this rapid variation in angle-of-attack effects the geometry of the blade-airflow interaction, and consequently, the collection of droplets and the aerodynamic efficiency of the blades (Flemming and Lednicer, 1986; Bragg, 1985). A second geometric effect concerns the scales of the helicopter rotors versus the fixed wings of typical aircraft; airflow will be a function of geometric measures of the rotors such as chord-length and span (Bragg, 1984; Lozowski and Oleskiw, 1983).

Once substantial accretions have occurred, asymetries in the icing profiles may lead to substantial alterations in blade balance as well as performance; the likelihood of asymmetric ice shedding, of different extent on each blade, will lead to a shift of the centre of mass away from the centre of rotation. Resulting vibrations could be severe and would result in enormous stresses placed on the rotor and control systems possibly leading to loss of control of the helicopter (Lozowski et al. 1979; Lake and Bradley, 1976).

Because of lower altitudes and airspeeds than fixed wing aircraft, helicopters encounter a different set of environmental conditions which affect the physics of the icing process. Liquid water contents, air temperature and pressure all vary as a function of altitude; collection efficiency and freezing fraction vary as a function of these parameters and airspeed.

Due to the complexity of the icing process on helicopters, it is clear that a simple model of helicopter icing of reasonable utility is exceptionally difficult to develop. The icing process, already considerably complex, is further confounded by the mechanical and aerodynamical properties of helicopter flight. Some approaches to this problem will be discussed in Section 4. Recommendations for the specific problem of icing climate assessment will be addressed in Section 5.

3. CLIMATOLOGY OF AIRCRAFT ICING IN CANADA

The following sections discuss: (1) the basic data available concerning aircraft icing and related cloud microphysical parameters, and (2) existing analyses of the extent of the aircraft icing problem in Canada. The latter portion is necessarily largely anecdotal, as little information on this topic is available in the literature.

3.1 Data Sources

Jeck (1986) provided a summary of airborne cloud physics projects from 1974 through 1984, with special emphasis on those projects in which measurements of liquid-water content, droplet sizes and hydrometeors were obtained from clouds above the melting level. Table 3-1 summarizes those studies with data that pertain to the eastern coastal areas of Canada. Details of the flights are given in Jeck (1985); that report summarizes data-availability for individual aircraft in each of the projects. It might be possible to expand the database further based upon review of that document. At least some of this information includes concurrent observations of icing type and severity (e.g. Cohen, 1983 - AFGL Icing); this represents a potential database for the verification and calibration of the selected candidate models identified in the present study. In addition, other groups outside of North America have undertaken icing research; Hoffmann et al. (1986) presented the results of a study of the relationship between ice accretion thickness on standard cylinders as a function of cloud parameters (liquid-water content, temperature, particle phase and size, altitude, along-flight distance, cloud type and cloud cover). This information would likely be quite useful in checking the logic of any procedure adopted and also for model calibration.

Table 3-1

Airborne Cloud Physics Experiments
Based on Jeck (1986)

PROJECT	DATE	LOCATION	PARTICIPANTS
Chinook Helo Trials	Jan-Mar 1984	Nova Scotia	RAF/Boeing Vertol
NEWS	Nov-Dec 1983	NE U.S.	NCAR
NEXRAD Support	June-Aug 1983	Massachusetts	UND
NEWS	Dec-Jan 1983	NE U.S.	NCAR
NRL Icing	Mar-Apr 1981	E U.S.	NRL
AFGL Icing	Mar-Apr 1981	NE U.S.	USAF/AFGL
LSCS	Mar-Apr 1981	NE U.S.	USAF/AFGL
AFGL Icing	Jan-May, Oct, Dec 1980	NE U.S.	USAF/AFGL
Summer Cumulus	June-July 1978	Ontario	AES
Summer Cumulus	June-July 1977	Ontario	AES
WX	Jan-Oct 1976	E U.S.	MRI,USAF/AFGL,
WX	Jan-June 1975	E U.S.	USAF/AFGL
WX	Jan-June 1974	E U.S.	USAF/AFGL

ABBREVIATIONS

AES - Atmospheric Environment Service (Canada)
AFGL - Air Force Geophysics Laboratories (U.S.)
LSCS - Large Scale Clouds Systems
MRI - Meteorology Research Inc.
NASA - National Aeronautics and Space Administration (U.S.)
NCAR - National Center for Atmospheric Research (U.S.)
NEWS - New England Winter Storms
NEXRAD - Next Generation Weather Radar
NRL - Naval Research Laboratory (U.S.)
RAF - Royal Air Force (U.K.)
UND - University of North Dakota
USAF - United States Air Force
WX - Weather

3.2 Analysis

Climatological information on the aircraft icing hazard over marine areas is limited. Much of the available information is in the form of subjective opinions expressed by persons involved in offshore operations rather than strictly objective measures. Additional information is anecdotal, referring to particularly unusual or severe cases within operational experience. Indeed, this lack of information is one of the primary motivations for the current study: to propose a procedure to obtain more detailed and complete climatological data concerning the aviation icing hazard in Canadian east coast regions. In this section, the information that is currently available in terms of operations experience and studies in the literature will be summarized.

A number of studies have detailed the conditions that would likely have an impact on aviation interests; much of this information was reviewed in Section 2. Additional details have been provided by studies of aircraft performance degradation under icing conditions. Dietenberger (1984) showed that ice accretions on the order of 0.1 mm over the entire wing would result in severe reductions in the rate of climb for a single-engine general aviation aircraft; higher accretions would require that the stall margin be reduced to unsafe values to climb at all. His analysis suggested that 10-35% weight reductions from the ice-free aircraft load would be required to preserve the rate of climb and an adequate stall margin. Landing manouvers would require a 6-15% increase in airspeed and 46-90% increase in thrust over ice-free values to maintain a constant angle of descent for 0.1 mm of ice rising to 11-22% increases in airspeed and 100-180% increases in thrust for accretions of 0.5 mm across the wing surfaces. These conditions would result in increases in the rate of descent equivalent

to the increases in airspeed. An alternative would be to decrease the angle of descent in order to maintain a constant rate of descent; this would require increases in thrust of 55-112% for 0.1 mm of ice and 121-209% increases in thrust for accretions of 0.5 mm.

Sand et al. (1984) and Cooper et al. (1984) reported the effects of icing on a research airplane (a Beechcraft Super King Air twin-engine turbo-prop). This airplane is larger and heavier with more power reserve than the single-engine aircraft examined above. Table 3-2 summarizes the results of those flights for 3 icing encounters. Generally, accumulations on the leading edges of the airfoils lead to limited degradation in flight performance given the reserve capacity and de-icing capabilities of the aircraft. However, in the case where larger droplets contributed significantly to the ice accretion, flight degradation was significant and required diversion from the icing conditions. The authors theorized that this degradation was due to runback water freezing on unprotected wing surfaces; as noted above, small roughness elements on airfoil surfaces can lead to a dangerous loss of aircraft performance. Such conditions could occur in regions of significant vertical cloud development (well-developed cumulus or moist flow upwind of mountain barriers) but would be unusual in Canadian east coast regions. Mitten et al. (1985) concluded that a similar aircraft (Beechcraft King Air BE-20) which is in use by Atlantic Airways for aerial reconnaissance of sea ice and icebergs would be grounded for only the most severe icing conditions, a rare occurrence offshore Newfoundland.

Ice accretion on helicopters represents a different problem; no civilian helicopters are presently certified for flying in icing conditions. Private offshore operators have indicated that they are restricted to visual flight rules (VFR) conditions. Consequently, downtime due to icing is viewed within the broader context of limitations due to the occurrence of instrumented flight rules (IFR) conditions. Military personnel responsible for east coast offshore

Table 3-2

3 Cases of Ice Accretion on Fixed-wing Aircraft Resulting in Flight Performance Degradation

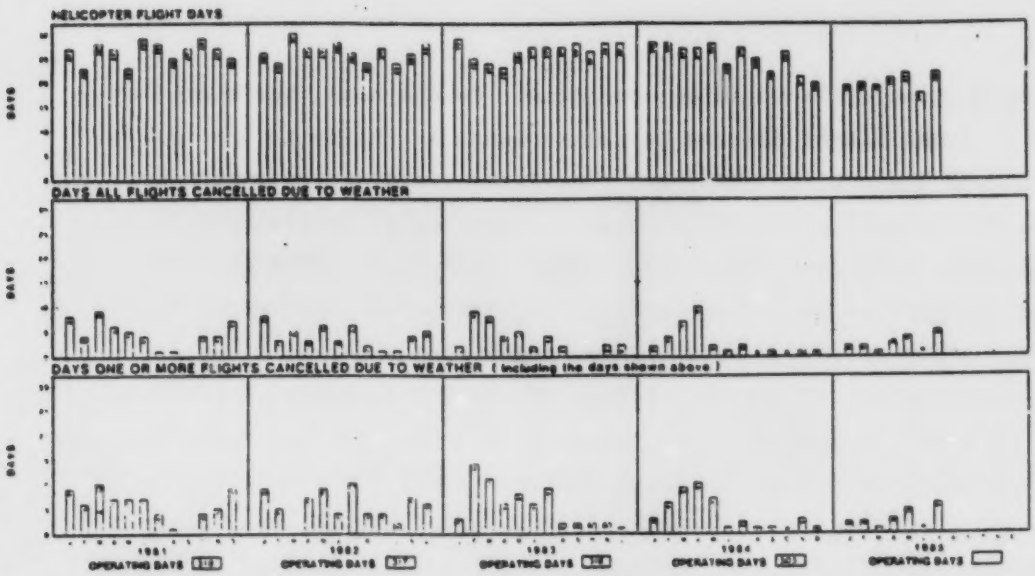
CASE	July 5, 1978	March 3, 1980	Feb 26, 1982
FLIGHT CONDITIONS	Cumulus Clouds LWC .23 g/m^3, T -12°C D 18 m	Upwind Sierra LWC .2-.3 g/m^3 T -7°C D 14-18 m	Upwind Sierra LWC .2-.25g/m^3 T -9°C D 18 m, many 40-300 m
POTENTIAL ICE ACCRETION	24 cm	14 cm	4 cm
LEVEL FLIGHT			
% Max Power Low Speed			
No Ice	29%	36%	33%
Ice	43%	50%	79%
% Max Power High Speed			
No Ice	43%	64%	48%
Ice	93%	86%	LEVEL FLIGHT IMPOSSIBLE
% Max Speed			
No Ice	100%	100%	100%
Ice	79%	95%	71%
DESCENT			
% Max Power			
No Ice	14%	33%	19%
Ice	57%	43%	64%
ASCENT			
% CLIMB RATE			
No Ice	100%	100%	100%
Low Speed	88%	77%	33%
High Speed	20%	55%	CLIMB IMPOSSIBLE

operations have indicated that icing on helicopters is a definite problem due to the frequent occurrence of freezing fog. Despite this, icing was not seen as a significant contributer to downtime although specific information was not available to this study.

A number of evasive manouvers are available to the helicopter pilot experiencing icing offshore, including:

- increase altitude to escape icing cloud;
- reduce altitude to take advantage of relatively warmer waters to promote melting and shaking off of accretions;

These manouvers are particularly effective in circumventing typical supercooled fog icing conditions found in the east coast nearshore environment, where an upflow of cool air produced by easterly winds frequently results in a narrow band of icing cloud extending a short distance from the coast (Mitten et al., 1985). Freezing rain, a less common condition particularly offshore, prevents operations if its occurrence is specified along the flight path since the resultant rapid accretion rate would quickly exceed the aircraft's ability to maintain flight. Mitten et al. (1985) presented the only information available in the literature on helicopter downtime due to weather (Figure 3-1). These data include all weather related cancellations such as freezing precipitation, reduced visibilities and ceilings and high winds. Based on this information, it is apparent that cancellations due to freezing precipitation are relatively rare offshore Newfoundland, although cancellations due to other weather-related causes are fairly frequent (~30% in winter). Brown and Roebber (1985) reported an investigation conducted by Boeing in the winter of 1983 of over-land helicopter icing based on flights from Shearwater, Nova Scotia. Liquid water contents were generally less than 1 g/m^3, with icing reported through a wide range of temperatures, the most severe occuring in the range 0° to -11^oC. Lake and Bradley (1976) reported engine torque rises resulting from ice accretion at temperatures warmer than -5^oC that were rapid enough to exceed the capabilities of the aircraft before a full



Charts indicating helicopter operations flight days and occurrence of cancellations due to weather (courtesy of Mobil Oil Canada, Ltd.)

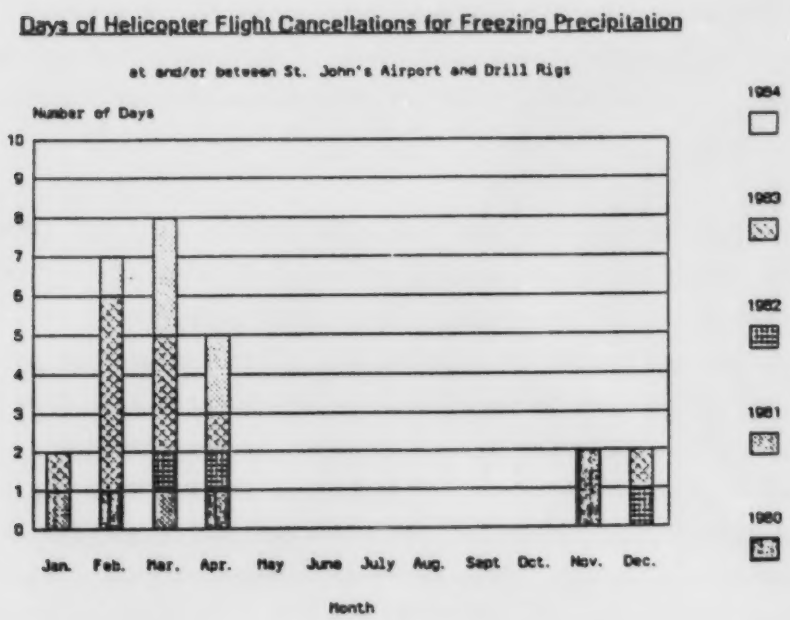
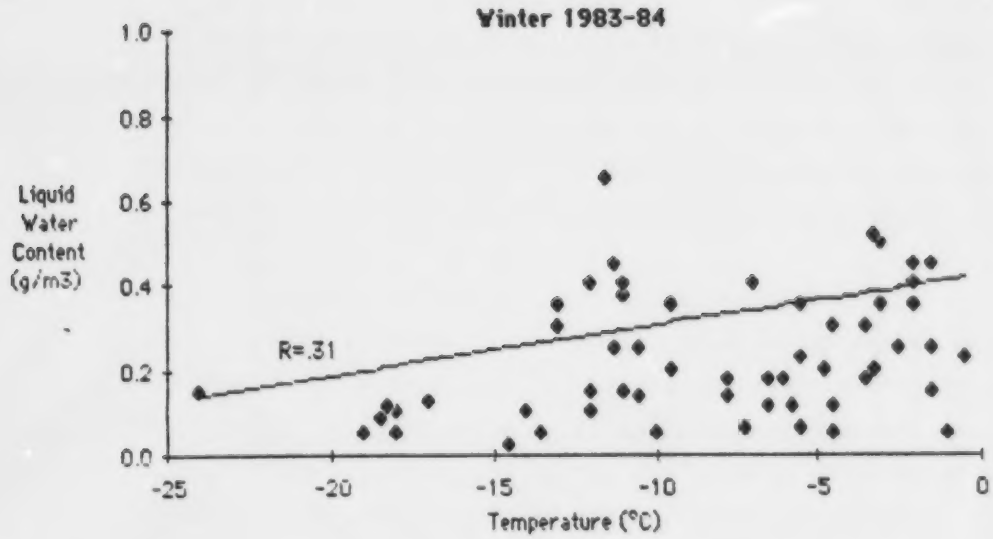


Figure 3-1: Helicopter downtime due to weather (from Mitten et al., 1985).

de-icing heating cycle could be completed. In one case, ice accretion prevented level flight despite large increases in engine torque (85% of maximum) and blade pitch (80%) and the flight was diverted within 60 seconds of the encounter. This incident occurred at an altitude of approximately 5000 feet; however, at lower altitudes (~2000 feet) similar though less severe experiences were reported with torque increases of up to 60% of maximum occuring within a period of 10 minutes as a result of ice accretion. In another instance, a pilot was unable to climb through an icing cloud at 3000 feet despite operating at 100% of maximum power. Lake and Bradley (1976) found no clear relationship between icing severity as defined by liquid water content and performance degradation, although there was some tendency for small power increases to be associated with lighter icing conditions. This experience appears to contradict the results of Bragg and Gregorek (1982) and Flemming and Lednicer (1986) who found that the degradation in rotor performance as defined by increases in blade drag was approximately linearly related to liquid water content. However, Flemming and Lednicer (1986) found that their theoretical predictions of increases in torque resulting from ice accretions did not correlate well with artificial icing data.

Operational experience has shown that significant helicopter icing rates are also possible in marine clouds, including at least one case of heavy icing (~5 cm) occurring within 15 minutes (Brown and Roebber, 1985). In the winter of 1983-84, Boeing in conjunction with the RAF conducted flight trials into known icing conditions in flow off open water near Shearwater, Nova Scotia to test the de-icing capabilities of Chinook helicopters. Information on drop size distribution and liquid water content was collected for a variety of temperature conditions (Craig, 1988, personal communication). The results of these trials are plotted in Figure 3-2. In general, icing was marginally more frequent and associated with higher liquid water contents at temperatures in the range 0 to -10°C, although icing was



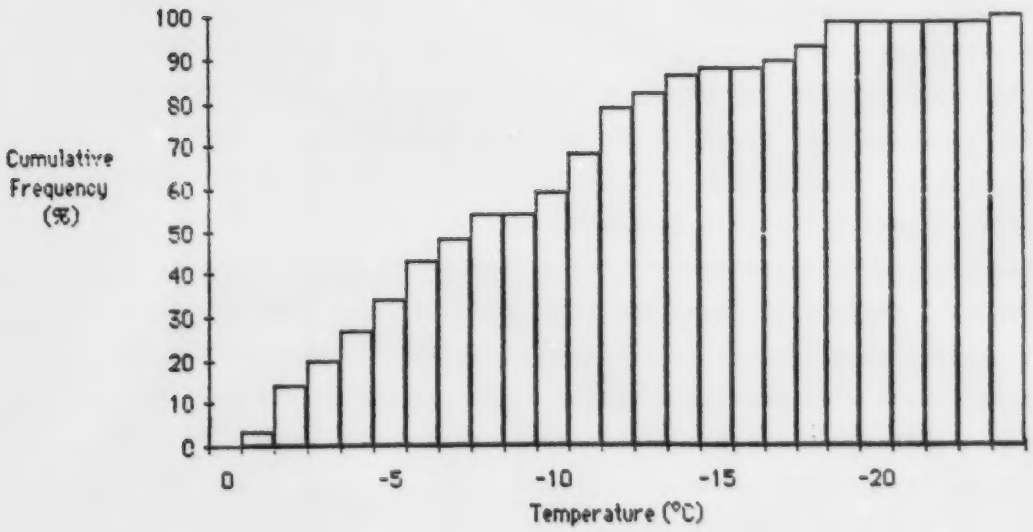
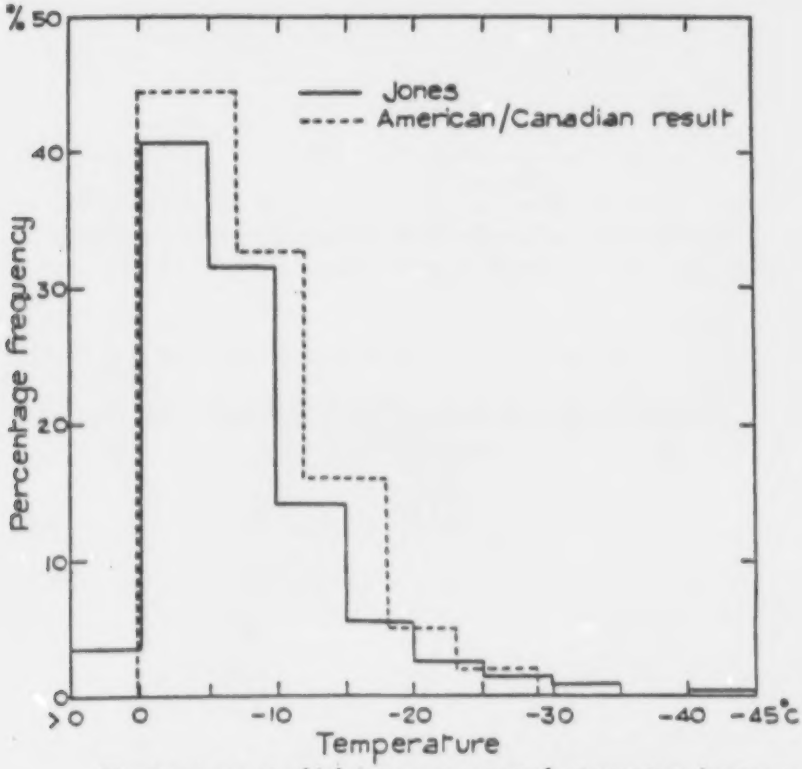


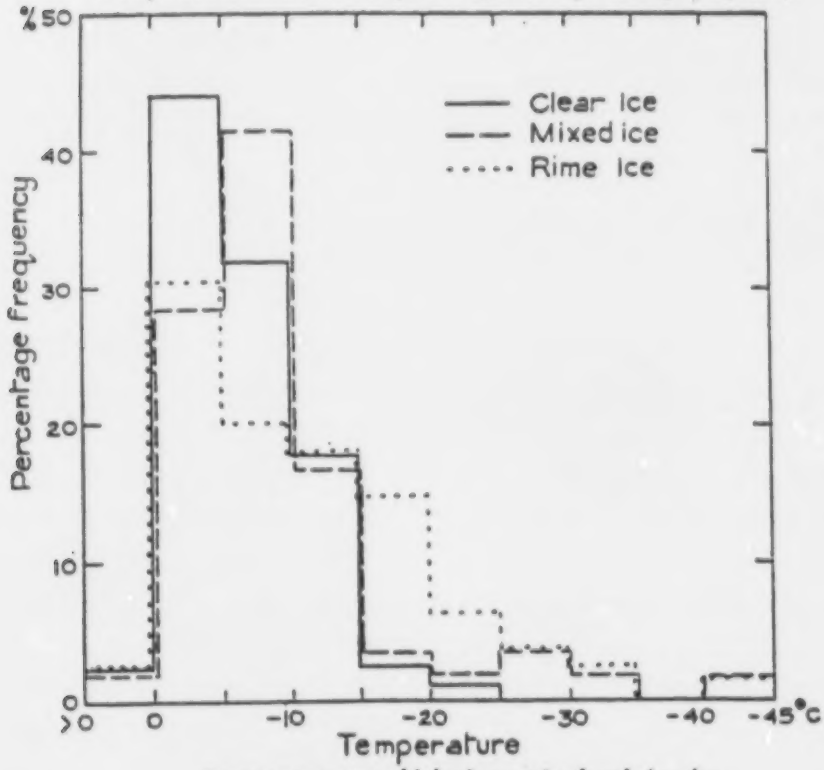
Figure 3-2: Liquid Water Content and cumulative frequency of icing occurrence as a function of air temperature.

encountered at temperatures as cold as -24°C; unfortunately, no information on ice accretion rates or relative severity was collected simultaneously. A total of 56 icing events were observed out of 120 cloud penetrations; 9 cases of clear icing were reported, and on the one occasion where a flight over open ocean was conducted, significant icing occurred. These data may be of some use in calibrating models of drop-size distribution and liquid water content in icing clouds, although flights into severe icing conditions were restricted.

The RAF Handbook on Weather forecasting contains additional summaries of the temperature, liquid water content, droplet sizes and airmass characteristics associated with icing clouds. Figure 3-3 summarizes the percentage frequency of icing reports falling within certain temperature ranges. It can be seen that icing, when it occurred, was most frequent at temperatures warmer than -10°C and diminished rapidly at lower temperatures. Ice accretion severity as a function of cloud type was also reported (Table 3-3). High rates of icing are associated with cumulus type clouds, but also with some layer types of cloud, probably due to their greater horizontal extent. Table 3-4 indicates icing severity as a function of frontal type based on 37,746 aircraft reports, of which 582 (1.5%) reported icing; moderate to heavy icing does not appear to be strongly dependent on frontal characteristics. Clearly the individual character of the clouds cannot be summarized in a convenient synoptic form. Tables 3-5 and 3-6 summarize the liquid water content and drop size characteristics of icing clouds. These data show that layer and mid-level type clouds in general contain considerably less liquid water than convective clouds; the latter clouds also exhibit a tendency towards larger mean volume drop sizes, although the other cloud types can produce large drop sizes (mean volume diameters greater than 30μm).



Temperatures at which icing was reported - percentage frequency



Temperatures at which clear, mixed and rime ice were reported - percentage frequency

Figure 3-3: Percentage frequency of icing reports and icing type as a function of air temperature (RAF Handbook on Weather Forecasting).

Table 3-3

Number of Reports of Icing As a Function of Cloud Type
(Source: RAF Handbook on Weather Forecasting)

Cloud Type	Rime ice			Clear ice			Total reports	
	Light	Moderate	Heavy	Light	Moderate	Heavy	Ice	No ice
Stratus	0	0	0	0	0	0	0	88
Stratocumulus	57	30	5	5	0	0	97	114
Cumulus	35	11	8	15	10	3	82	19
Cumulonimbus	0	2	2	1	0	2	7	0
Nimbostratus	11	11	3	0	2	3	30	3
Altostratus	9	4	0	2	1	0	16	85
Altocumulus	49	20	3	5	3	0	80	88
Altocumulus and altostratus	30	5	1	1	0	0	37	47

Table 3-4

Number of Reports of Icing As a Function of Frontal Situation
(Source: RAF Handbook on Weather Forecasting)

Synoptic characteristics	Intensity of icing			Total
	Light	Moderate	Heavy	
Warm front	140	37	6	183
Cold front	107	26	2	135
Occlusion	44	14	2	60
Warm air mass	33	10	3	46
Cold air mass	116	35	7	158

Table 3-5

Cumulative Percentage Frequency Distribution of LWC
(Source: RAF Handbook on Weather Forecasting)

LWC (gm^{-3})	Cloud Type Convective	Layer	Medium
	% Measurements < LWC		
0.1	17.2	19.2	59.3
0.2	34.0	53.8	91.5
0.3	51.1	76.9	98.6
0.4	61.4	91.0	100.0
0.5	72.5	98.1	..
0.6	82.8	100.0	..
0.7	88.3	..	..
0.8	90.6	..	..
0.9	94.5	..	..
1.0	97.2	..	..
1.2	99.0	..	..
1.4	99.5	..	..
1.63	100.0	..	..
No. of Obs.	215	156	140

Table 3-6

Cumulative Percentage Frequency Distribution
Of Median Volume Drop Diameter (d)
(Source: RAF Handbook on Weather Forecasting)

d (μm)	Cloud Type		
	Convective	Layer	Medium
	% measurements < d		
6	..	1.9	0.7
9	2.4	20.1	5.2
12	11.0	51.0	17.0
15	25.0	74.3	37.0
18	40.4	85.5	54.9
21	57.6	93.1	69.6
24	76.4	96.2	84.5
27	89.9	97.5	88.9
30	93.2	98.8	90.4
35	95.6	99.4	91.1
40	..	100.0	..
45	97.5	..	..
50	98.1	..	97.1
No. of Obs.	208	159	135

4. AIRCRAFT ICING MODELS AND FORECAST TECHNIQUES

Icing models that have appeared in the literature can be classified into two general categories:

(1) Research models - computer codes that have been developed to study in detail the physical processes involved in aircraft icing.

(2) Diagnostic models - procedures or codes developed for operational use, i.e. to forecast the severity and type of icing likely to occur on aircraft.

Diagnostic models have been limited in scope to estimating ice accretion on fixed-wing aircraft since helicopters have not been certified for full IFR flight conditions. Essentially, an ice/no-ice forecast is presently all that is required for the purposes of helicopter flight; as the demands of civilian and military offshore and arctic flight requirements have expanded, so has the need for increased theoretical knowledge of rotor-icing. However, at present there are no operational procedures for forecasting helicopter icing beyond the ice/no-ice level. Thus, the discussion of helicopter icing will be confined to Section 4.1 which deals with research models, while Section 4.1 and 4.2 will both contain elements concerned with the modelling of fixed-wing ice accretion.

4.1 Research Models

Much of the effort in this area has been spearheaded by the NASA Lewis Research Center's aircraft icing analysis program initiated in 1978 (Shaw, 1984). Brown and Roebber (1985), in their review of aircraft icing models, identified three separate phases of research modelling effort:

Phase I: modelling of generalized ice accretion;
Phase II: modelling of airfoil ice accretion;
Phase III: prediction of aerodynamic performance degradation resulting from airfoil ice accretion.

Phase I and Phase II models have been reviewed to some extent by Brown and Roebber (1985); the discussion in this report will therefore centre mainly on Phase III developments, although brief summaries of the earlier work will be included for completeness. Table 4-1 lists the work in the three phases uncovered by this review.

4.1.1 Phase I: Generalized Ice Accretion Models

Cansdale and McNaughton (1977) and Lozowski, Stallabrass and Hearty (1979)

These models were developed with a view towards developing insight into the physics of rotor blade icing; therefore, runback effects were included although the geometry was simplified to the problem of a non-rotating cylinder. Time dependent effects were excluded and output was in the form of icing rate as a function of angle around the cylinder. Mixed accretion effects (supercooled droplets and ice crystals) were also included in order to test whether this condition could lead to rapid increases in rotor blade icing rates. Lozowski et al. (1979) then verified their model against a large number of experimental cylinder icing tests performed over a range of icing conditions. Principal conclusions of the work with important implications for the helicopter icing problem were:

- mixed icing is not a serious problem for high speed, low temperature flight or lower speed, high liquid water conditions since the ice crystals do not adhere well to the accretion surface (and may in fact erode accretions);

Table 4-1

Ice Accretion Research Models and Observations

PHASE I: Generalized Ice Accretion Models

Cansdale and McNaughton (1977)
Lozowski, Stallabrass and Hearty (1979)
Ackley and Templeton (1979)
Bain and Gayet (1982)
Bain, Gayet and Soulage (1984) - observations
Gayet, Bain and Soulage (1984) - observations
Makkonen (1984)

PHASE II: Airfoil Icing

Le Sueur (1978) - observations
Cohen (1983) - observations
Lozowski and Oleskiw (1983)
MacArthur (1983)
Bragg (1984)
Bragg (1985)
Hansman (1985)
Sweeney and Cohen (1985) - observations
Hoffman, Roth and Demmel (1986) - observations
Jeck (1986) - observations

PHASE III: Aerodynamic Performance Degradation

Kloner (1970)
Lake and Bradley (1976) - observations
Cooper, Sand, Politovich and Veal (1984)
Dietenberger (1984)
Korkan, Cross and Miller (1984)
Korkan, Dadone and Shaw (1984a,b)
Sand, Cooper, Politovich and Veal (1984)
Korkan, Cross and Cornell (1985)
Flemming and Lednicer (1986)

- warm temperature ice accretion is dominated by runback effects, and may be most serious in the low pressure region on the upper portion of the airfoil where even small amounts of ice may drastically reduce performance.

Ackley and Templeton (1979)

These authors addressed the problem of the icing of a non-rotating cylinder as a simplification of the airfoil icing problem. Time-dependent effects such as the impact of changing accretion profile on collection efficiency and the overall heat transfer coefficient are included. The model assumes that the overall accretion is distributed in such a way that the surface is always a smooth ellipse with the minor axis equal to the cylinder diameter and aligned perpendicular to the growing accretion. Runback effects were neglected. Output was in the form of profiles of ice thickness and tables of energy fluxes and collection efficiency at each time stop. To simulate the variation of velocity along the rotor blade, options are included in the model to view accretion parameters as a function of velocity (radial position) along the blade. Principal conclusions of the study were:

- cross-section and object shape can change considerably with changing meteorological conditions, especially at higher temperatures; non-elliptical shapes may significantly effect the flow field and collection efficiency;

- boundary layer effects not included in the model may be significant as they relate to collection efficiency and heat transfer.

Bain and Gayet (1982)

This work represents an extension of Lozowski et al. (1979) to include variable ice density effects based on Macklin (1962). Output additonal to Lozowski et al. (1979) includes ice density versus angle around the cylinder. The inclusion of this effect resulted in ice thicknesses strongly dependent upon the cloud droplet spectrum;

however, this effect was not sufficient to simulate observed ice deposit shapes.

Makkonen (1984)

A time-dependent numerical model of icing was applied to the problem of accretions on overhead wires. This procedure included the effects of wet and dry growth processes through the thermodynamic balance on the icing surface. The results showed that a transition from wet to dry growth occurs under constant atmospheric conditions, and that the formation of ice loads is related in a complicated and time-dependent way to temperature, liquid water content, impact velocity and drop-size.

4.1.2 Phase II: Airfoil Icing

Lozowski and Oleskiw (1983)

This model permits simulation of the time-dependent growth of dry ice accretions on an arbitrary, 2-D non-rotating airfoil. Consequently, the development was centred on the impingement characteristics of droplets on the airfoil surface. Ice accretion profiles were compared with experimental accretions with satisfactory results. A series of model tests showed that accretion profiles predicted by the model were significantly different for single-step and multi-step procedures; the latter procedure generally replicated experimental results more adequately. This result underlined the importance of time-dependent effects on airfoil ice accretion.

MacArthur (1983)

This effort is an extension of the work of Lozowski et al. (1979) and Ackley and Templeton (1979); the model predicts the ice growth rate distribution around the leading edge of the airfoil by solving the thermodynamic energy balance equation. The model has an extended routine for computing heat transfer based on laminar, transitional and turbulent boundary layer development which attempts to account for surface roughness effects. Potential flow analysis is used to compute droplet trajectories and resultant local collection efficiency characteristics as the accretion proceeds. Comparison with available experimental data indicated that the model significantly underpredicts observed local maximums in heat transfer for both rime and glaze icing conditions.

Bragg (1984)

This study was directed towards the prediction of droplet trajectories about an airfoil, and the effect of geometric properties of the airfoil on the overall flowfield. The analysis showed that the droplet inertia parameter and airfoil angle of attack were the most significant factors affecting droplet impingement. The droplet inertia parameter measures the relative importance of inertial versus drag forces; as the droplet inertia increases, the impingement increases. The angle of attack governs the position of droplet impingement on the airfoil; also, the total mass of droplets impinging on the airfoil increases as the angle of attack increases. Additional effects observed were:

- impingement increases with decreasing airfoil leading edge radius;
- collection decreases with increasing maximum airfoil thickness;

- extent of impingement increases on the upper and decreases on the lower airfoil surfaces as the maximum camber of the airfoil is increased.

These effects, along with the thermodynamics, determine the ice accretion shape and the relative magnitude of performance penalties due to icing.

Bragg (1985)

This paper describes a methodology for predicting rime ice accretion on airfoils; as such, the primary consideration is the accurate specification of time dependent droplet impingement. In order to model the impingement characteristics of a distribution of droplet sizes, effective droplet characteristics were derived by combining results for several droplet sizes. The computation procedure is then a 3-step process: determine the flowfield, determine droplet trajectories and impingement characteristics and calculate the rime ice shape. This procedure is repeated at each time step. Comparisons of model results with experimental rime ice accretions showed substantial agreement. Suggestions for additional improvement included:

- simulate viscous effects on the flowfield by adding boundary layer calculations;
- generalize for compressible fluid flow;
- establish method to compute low-temperature rime ice density;
- generalize for glaze-ice by including thermodynamics of ice accretion.

Hansman (1985)

The intent of this work was to investigate the effect of droplet shape and size on droplet impingement. Code was developed to account for the effect of non-spherical droplet shape due to hydrodynamic deformation; the code was then used to study the effect of droplet size

on collection efficiency. It was determined that the droplet size distribution was an important factor in the impingement of droplets for cloud size particles. In particular, large drops represented a significantly greater threat than small droplets, implying that low liquid water content clouds, if comprised of relatively few large droplets, could present a significant icing hazard to aviation.

4.1.3 Phase III: Aerodynamic Performance Degradation

Kloner (1970)

A method is presented in this work for calculating the freezing rate distribution on an airfoil and thereby the general form of the ice accretion pattern. Potential flow, the thermodynamic energy balance, and runback effects are considered. The problem of predicting ice accretion shapes on an airfoil was the primary goal of the study; this was accomplished by considering the "freezing pattern" resulting from the initial freezing rate distribution rather than evaluating the time integral of the freezing rate. Major simplifications made in conducting this work included:

- droplet collection is based on that of a clean airfoil using potential flow theory;
- ice accretion is not time-dependent, that is, the initial freezing pattern is taken to be representative at later times.

However, the work was able to demonstrate the flight conditions under which irregular accretions (horns) develop and their location on the airfoil. That information is important in assessing potential flight degradation resulting from ice accretions.

Cooper et al. (1984) and Sand et al. (1984)

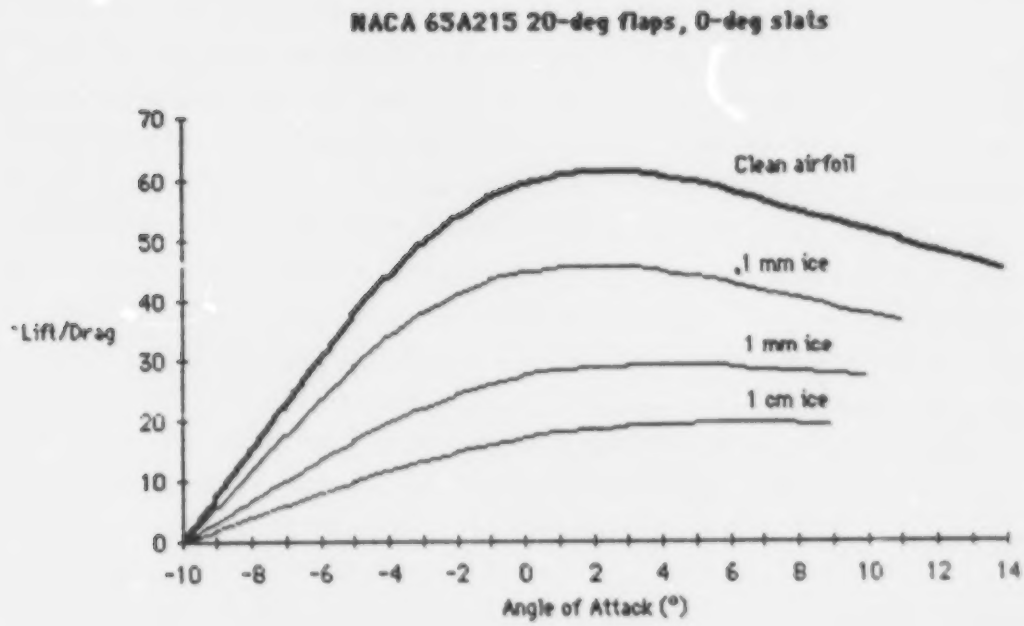
These papers represent an effort to directly assess the effects of icing on fixed-wing aircraft performance. Measurements of un-iced versus iced rates-of-climb for various meteorological conditions were recorded. It was determined that the primary effect of icing was to increase the overall drag of the aircraft, while the effects on lift were minimal. Cases in which serious icing was experienced were not indicated by measures of liquid water content; those conditions were characterized by liquid water contents typical of modest icing conditions in combination with exceptionally large (40-300 μm) droplets, a result in agreement with the theoretical work of Hansman (1985).

Dietenberger (1984)

Steady-state flight equations were combined with empirical relationships of drag and lift penalties derived from wind tunnel experiments to assess take off and landing procedures under icing conditions. Procedures specified to maintain safety when ice removal and avoidance were not possible included:

- reduction of maximum gross weight at take-off in proportion to the maximum loss of lift;
- increase of thrust and landing speed inversely proportional to the square root of the maximum lift loss.

These procedures were shown theoretically to maintain a safe stall margin and climb rate at takeoff and a safe stall margin and descent rate at landing for single-engine, general aviation aircraft and Boeing 727 transport jets for ice accretions of up to 1 mm thickness. Figure 4-1 shows the application of this technique to the performance characteristics of a generic airfoil and a single-engine general aviation aircraft.



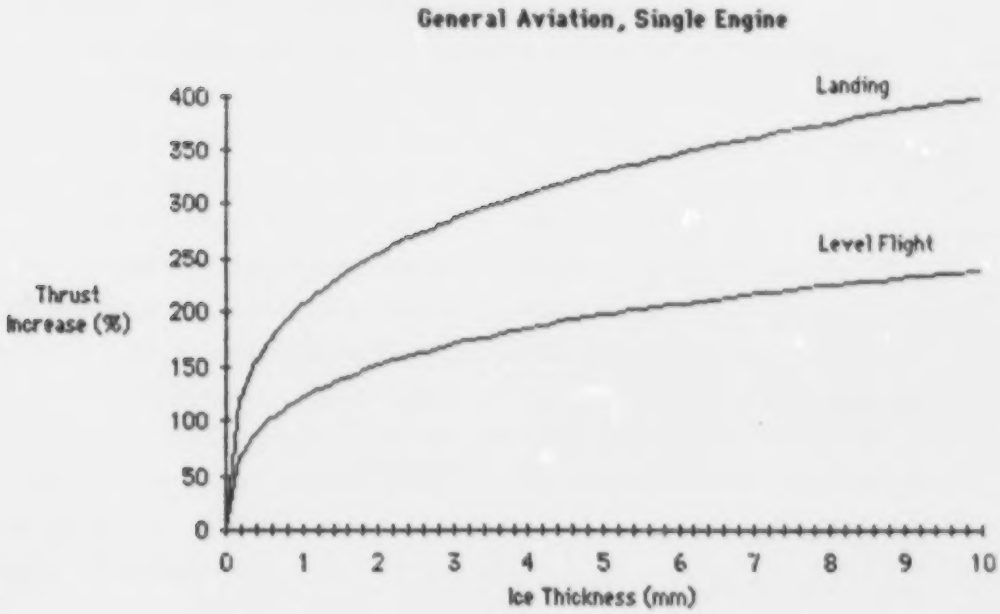


Figure 4-1: Lift-to-drag ratio and required thrust increase as a function of icing.

Korkan, Cross and Miller (1984)

A model helicopter was used to study helicopter performance under simulated icing conditions. A generic ice shape was attached to various radial locations along the rotor blade, and performance data were collected under hover and forward flight conditions. Significant degradation (150% increase in torque to maintain constant thrust) was observed with ice acretions at 85% of the blade length; considerable additional degradation was found when the generic ice was applied along the span to the rotor tips. Consistently higher torque was required for forward flight than hover for any spanwise extent of icing. The range of experimental values was somewhat limited due to scaling considerations; it was felt that a larger rotor chord and a more powerful engine would allow for further expansion of the experimental results.

Korkan, Dadone and Shaw (1984a,b)

A theoretical ice accretion model was developed to compute performance degradation of propeller systems due to rime icing. The airfoil icing analysis of Bragg et al. (1981) was used in combination with initial conditions applicable to the rotor case to compute the water droplet trajectories. This process involved a Theodorsen transformation method to calculate the inviscid flowfield around the airfoil, which is then used to determine droplet trajectories and impingement rates and locations. The empirical correlation of Bragg and Gregorek (1982) was then used to determine the degradation in propeller performance due to increases in blade drag. Simplifications included:

- neglect of thermodynamic processes (rime icing);
- neglect of icing effects on lift;
- neglect of centrifugal/adhesion forces and kinetic heating on removing ice and vibrational effects due to shedding.

Levels of agreement between the theoretical and experimental results of natural icing encounters were considered acceptable, although the theoretically required thrust values were consistently high. Exclusion of the decambering effect due to ice accretion at the leading edge of the airfoil (which leads to a shift in the zero lift angle of attack) was noted as the probable cause of that error. Analysis of performance based on this model indicated that power increases of up to 24% would be required to maintain hover in a 5 minute icing encounter involving full spanwise accretions.

Korkan, Cross and Cornell (1985)

Wind tunnel tests were conducted to test the effect of simulated ice on a standard airfoil to measure its impact on lift, drag and pitching moment for use in helicopter performance analyses. The presence of ice on the leading edge of the airfoil created premature stall and reduction of lift capacity; in addition, drag was increased on the order of 200% and significant effects on the pitching moment were observed. These characteristics could lead to substantial difficulties in maintaining level flight and overall handling capabilities of an aircraft.

Flemming and Lednicer (1986)

Expanded information concerning the performance of rotorcraft under icing conditions was obtained in this study by testing 10 rotor models in a wind-tunnel under simulated icing conditions. Lift was reduced only slightly at low angles of attack but decreased by 20% at higher angles, while drag increased by a factor of 3 to 4 at low angles and was significantly worse at higher angles and liquid water contents. The oscillation of the airfoil was found to reduce the drag penalty without effecting lift loss. Empirical relationships were derived for

ice thickness and changes in lift, drag and pitching moment. This information was used to predict ice extent and torque rise in icing conditions; however, that analysis showed fairly unsatisfactory results.

4.2 Diagnostic Models

These models have generally been developed as forecasting aids for aviation meteorologists; as a result, input requirements are limited to standard surface and upper air meteorological observations and model physics are simplified and/or parameterized. Output is generally in graphical form. The advantages of such models for the purposes of assessing climitalogical ice accretion of aircraft are obvious: limited input data and minimal processing time requirements. The disadvantages are equally clear: simplifications of complex and highly non-linear processes may result in poor correspondence with actual experience. The applicability of a model to the stated objective of this study must be assessed primarily or the basis of the limitations of the climate database. Thus, the performance of the identified candidate models must be carefully evaluated vis-a-vis actual observations to properly determine the validity of its application to climatological studies.

Diagnostic models can be broadly categorized into two types: icing forecasts based on heuristic rules (e.g. AWS/USAF methodology) and freezing precipitation forecasts based on vertical profiles of temperature and humidity. A selection of these models, uncovered in the literature review, will be summarized below.

Jensen (1963)

This paper represents one of the earliest attempts at establishing a method of prediction of airframe icing conditions for operational use. However, as the methodology was developed primarily as a scheme for the prediction of large-scale cloudiness, the icing forecast procedure was viewed as a by-product of the cloud model; no verification of the utility of the scheme was presented. The icing procedure made use of empirical rules and techniques reported by the Air Weather Service (1960). The logic of the procedure is displayed in Figure 4-2. Cloud amounts in the 850 mb to 700 mb layer and 700 mb to 500 mb layer and temperature at 850 mb, 700 mb and 500 mb were used as input. The basic concept employed was that the lower the temperature below $0^{o}C$ and the greater the layer stability, the greater the likelihood of rime versus clear icing (the occurrence of mixed icing was taken to occur in the grey areas between these two conditions). As a result, the impact of cloud morphology (type, development, origin) and position within the cloud are only crudely considered, and the effect of the structure and motion of the aircraft on icing is neglected.

Lawford (1971)

This model was based on the work of Jensen (1963) with some modifications. Input data are limited to temperature, dewpoint depression and lapse rate in four layers: 850-770 mb, 770-700 mb, 700-590 mb and 590-500 mb. The basic premises of the model are based on the 1969 USAF AWSM Icing manual; the logic is outlined in Figure 4-3. Limitations to the model are identical to that of Jensen: cloud characteristics are grossly simplified and aircraft-dependent effects are not treated.

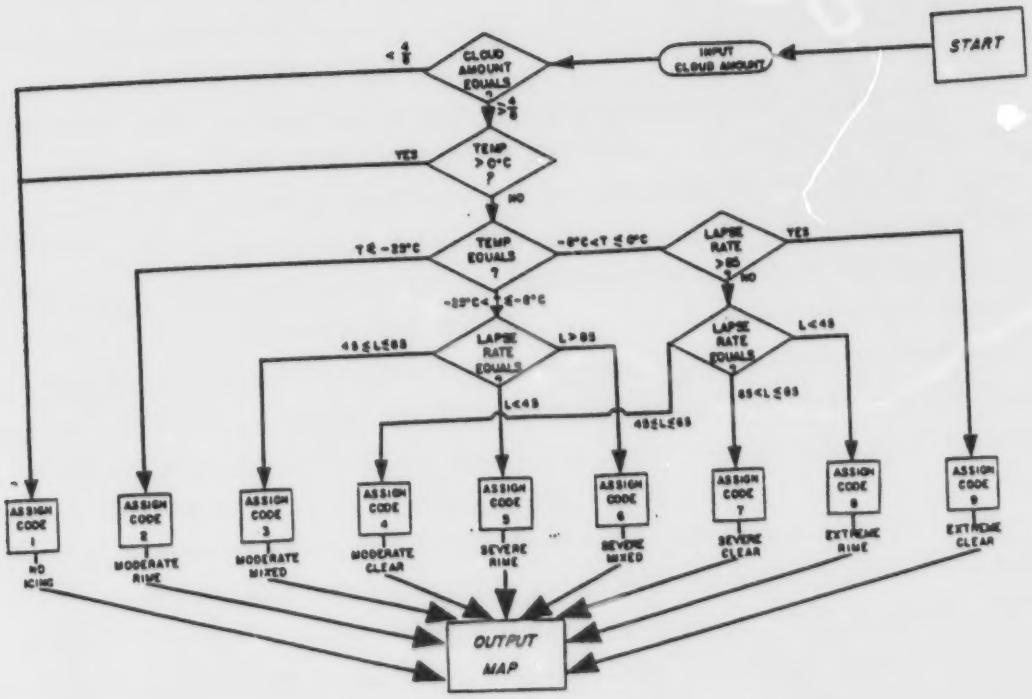
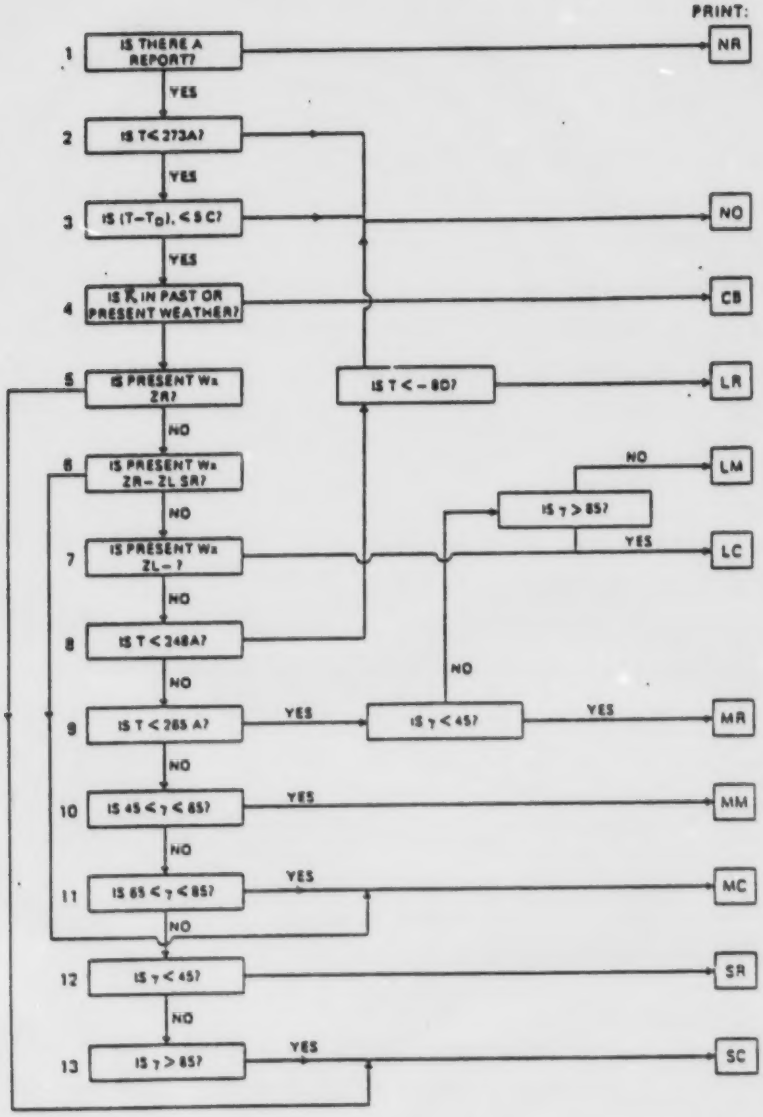


Figure 4-2: Aircraft ice accretion logic (Jensen, 1963).



LOGIC DIAGRAM

Figure 4-3: The sequence of decisions made in the diagnostic model of potential airframe icing for the levels between 850 and 700 mb. From Lawford (1971).

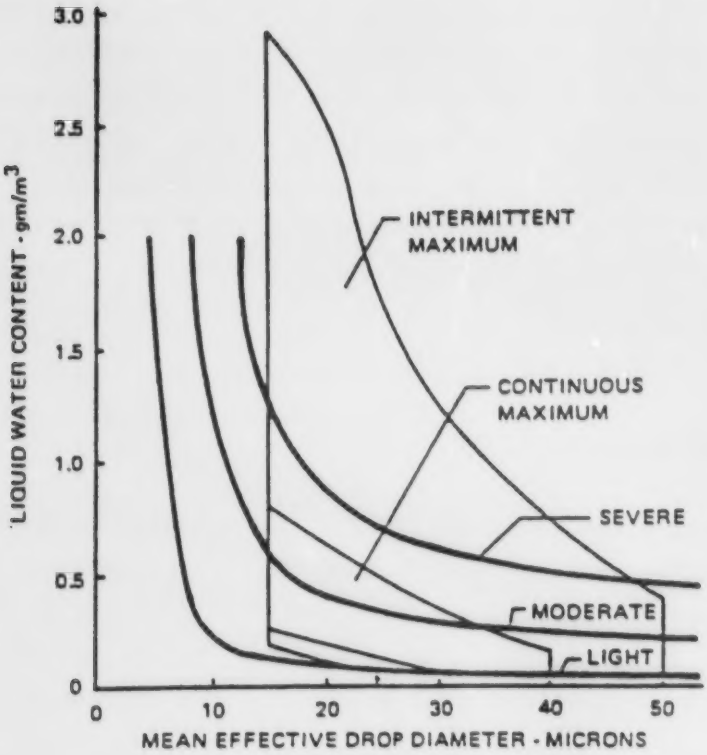
Newton (1978)

This paper represented an effort to define icing intensity based upon physical considerations; that is, an integrated approach to the reporting and prediction of icing intensity. As such, it did not present a methodology for the forecast of icing; rather, it established a procedure for the definition of icing severity that is easily incorporated into diagnostic forecast models. It represents a means of accounting for the effects of a given set of meteorological conditions on individual aircraft.

The approach is based on a definition of icing conditions which can be readily expanded into rates of accretion on an object of known geometric properties. The definition was first proposed in a 1945 Weather Bureau document, and later expanded by Lewis (1947) into accretion rates. The definition relates the intensity of icing to the rate of collection of ice at 200 mph on a circular cylinder 3 inches in diameter, as follows:

Trace	0.0 - 1.0 g/cm^2-hr
Light	1.0 - 6.0 g/cm^2-hr
Moderate	6.0 - 12.0 g/cm^2-hr
Severe	$\geq$ 12 g/cm^2-hr

Lewis defined a series of envelopes for these definitions as a function of drop-size and liquid water content (Figure 4-4). Newton (1978) demonstrated that a reasonable correspondence exists between these envelopes and the transport category envelopes (adopted as standards for the design and construction of aircraft weighing more than 12,500 pounds and most jets). Thus, a look-up table of severity-onset liquid water content values could be defined as a function of cloud type (layer, convective), flight level, temperature and airspeed. The occurrence of these liquid water contents could be forecast (hindcast) based on the simple cloud model of Best (1952) used in the 1969 USAF AWSM Icing manual, which required only information on the vertical structure of temperature and humidity. Icing severity would then be



Lewis definitions of icing intensity.

Figure 4-4

assessed based upon the comparison between the look-up value and the forecast liquid water content. The type of icing is somewhat problematical; the Air Force method indicates rime icing in layer clouds and clear icing in cumulus, yet data compiled by Clark (1948) and Bowden et al. (1963) among others showed that ice accretion type is a function of temperature and air speed for the same conditions of liquid water content and drop-size. Macklin (1962) defined a function from which it is possible to derive accretion density; however, this function was derived from data for which impact velocities are considerably lower than are found in aircraft icing encounters. Under most conditions, that expression would indicate clear ice formation with little or no rime accretions, in direct contradiction to experience (Perkins et al., 1957).

U.S. National Weather Service (NWS)

This review is based on Tucker (1983). The procedure followed by the NWS is subjective in nature and thus difficult to summarize. The forecaster must assimilate all applicable numerical guidance products and observations (Pilot reports, satellite photos, radar, soundings and surface weather) and assess the icing potential. The basic steps are as follows:

- establish the forecast freezing level;
- ascertain the presence of moisture above the freezing level;
- assess local influences on the supply of moisture;
- estimate the severity and type of the icing.

The final step is the most subjective, based largely on the forecaster's ability and experience. Some general guidelines used by NWS are as follows:

- Severe icing is generally associated with an area of steady surface precipitation (90% relative humidity at 700 mb) with 850 mb temperatures of $0^{o}C$. Freezing rain also indicates severe icing.

This type generally occurs below 8,000 feet. Icing type is considered to be mixed or clear in freezing rain;

- Moderate or moderate to severe icing is expected in areas of rain or snow showers (70% relative humidity at 700 mb) with accompanying temperatures from 0°C to -10°C. This type of icing is generally confined below 12,000 feet. Icing type is rime or mixed;

- Light icing occurs with 60 to 70% relative humidity at mid-levels and temperatures of -10 to -15°C. Icing type is rime.

Since forecasting of ice accretion is only one portion of an area forecast, the methodology followed is somewhat unsophisticated. The subjective nature of the scheme does not allow for straightforward implementation in a computer-based system.

Air Weather Service/United States Air Force (1980)

The AWS/USAF (1980) manual outlines several techniques designed to allow the forecasting of aircraft icing, ranging from detailed procedures involving the examination of soundings to more subjective methods.

The most detailed technique involves the examination of upwind or forecast soundings representative of identified areas of potential icing. Initially, the type of icing is determined by the lapse rate through the cloud layers; stable layers are assumed to indicate stratiform clouds and rime icing, while conditionally unstable layers indicate cumuliform clouds and clear icing. The severity of icing is then determined using an overlay (Figure 4-5) on the sounding. The severity curves are based on the work of Lewis (1947) (as described in Newton, 1978), using a cloud model developed by Best (1952) for specified conditions of altitude, temperature and airspeed.

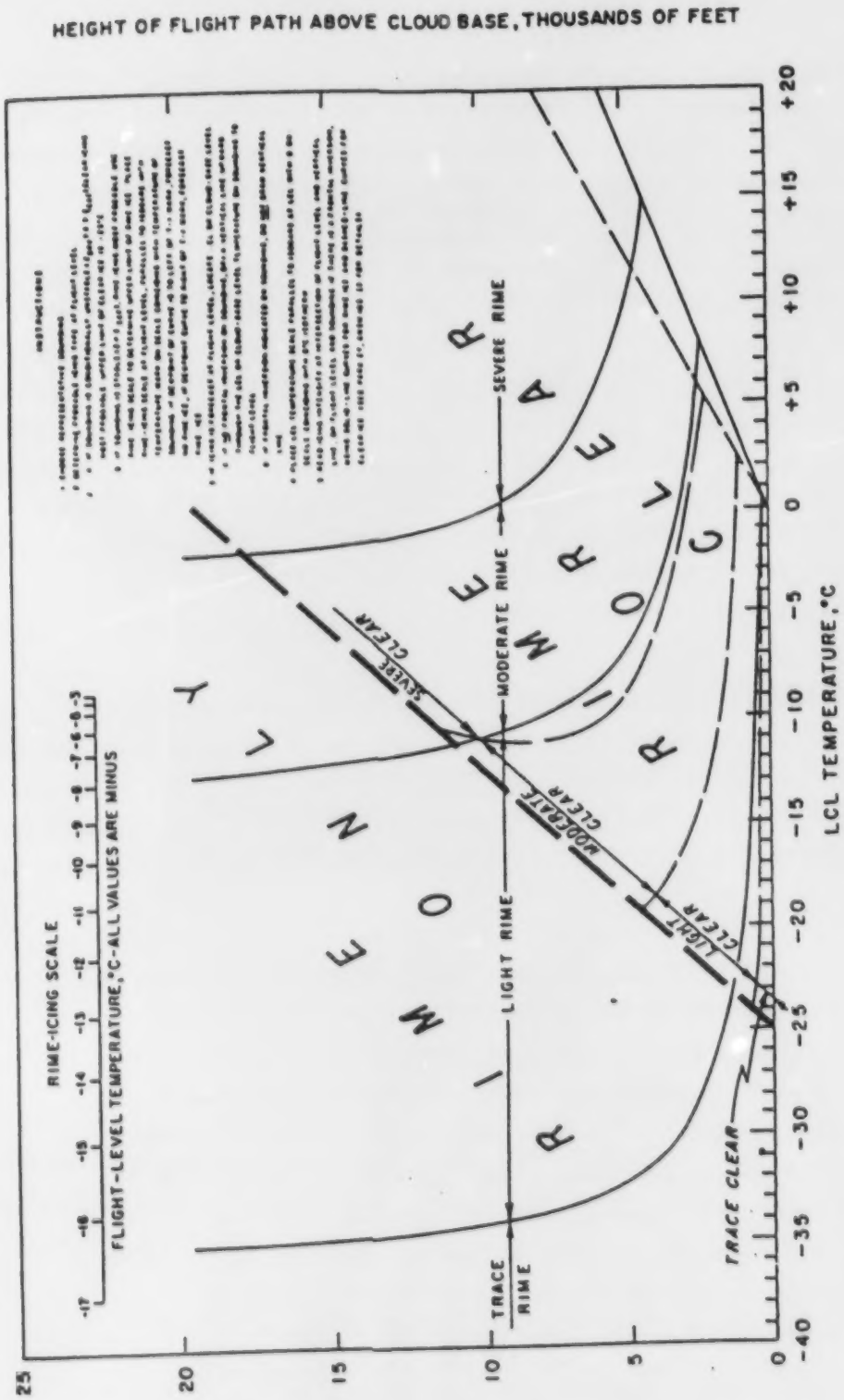


Figure 4-5: AWS/USAF (1980) overlay for ice accretion prediction.

The second method is limited to icing in stratiform clouds and is based upon considerations of the phase of water in the cloud. A nomogram (Figure 4-6) is used to determine the probable phase condition of the cloud particles based upon temperature and dewpoint conditions within the stratiform cloud. The technique is based on work conducted by Appleman (1954); a comparison is made of the degree of saturation with respect to ice and water to determine the relative proportion of ice crystals versus supercooled water droplets. An air temperature equivalent to the dewpoint value represents saturation with respect to water, 90% of the dewpoint approximates saturation with respect to ice and 80% of the dewpoint (the "Appleman Line") is the 95% limit of icing encounters based on empirical studies. In this way, a climatological probability of encountering rime icing is indicated, while the intensity of the ice accretion is not directly indicated.

Another method consists of a rule-based procedure (Table 4-2) based upon empirical studies of dewpoint depression and advection by Thompson (1955), the saturation considerations of Appleman (1954) and forecast experience. Input requirements are temperature and dewpoint depression data, cloud and precipitation information and a general synoptic description. These rules are used to predict the intensity and type of icing. For the purposes of this study, the input requirements for this procedure are all met by the climate database with the exception of the synoptic description. However, the synoptic information is only required if upper air data are unavailable; as a result, this procedure can readily be applied to the climate database. Since the icing information is descriptive rather than quantitative, however, it would not be possible to adjust the forecast to different flight conditions.

A method not published in AWS/TR-80/001 but, according to Tucker (1983), utilized by AWS detachments refers to rime icing in stratiform clouds. Input requirements are vertical profiles of temperature and dewpoint. Essentially, an empirical comparison is made between the

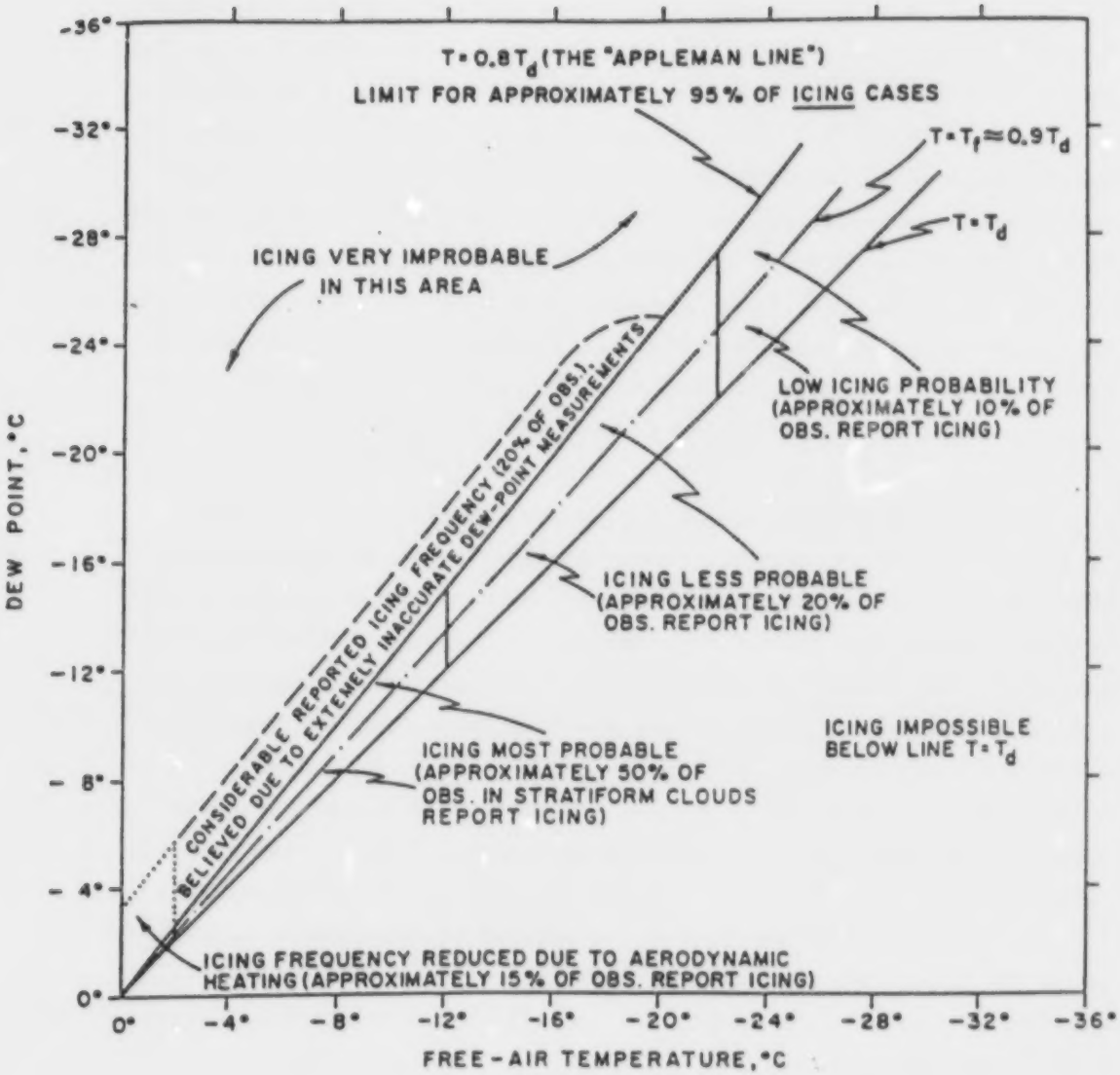


Figure 4-6: AWS/USAF (1980) nomogram for icing prediction.

Table 4-2

Rule-based Method
(Upper Air Data - Rules 1 to 2)

Rule 1*	T	T - Td	Forecast	Probability
a.	0° to $-7^{\circ}C$	$> 2^{\circ}C$	None	80%
b.	-8° to $-15^{\circ}C$	$> 3^{\circ}C$	None	80%
c.	-16° to $-22^{\circ}C$	$> 4^{\circ}C$	None	90%
d.	Lower than $-22^{\circ}C$	Any spread	None	90%

Rule 2*	T	T -Td	Advection	Icing forecast	Probability
a.	0° to $-7^{\circ}C$	$\leq 2^{\circ}C$	Neutral/weak cold air	Trace	75%
			Strong cold air	Light	80%
b.	-8° to $-15^{\circ}C$	$\leq 3^{\circ}C$	Neutral/weak cold air	Trace	75%
			Strong cold air	Light	80%
c.	0° to $-7^{\circ}C$	$\leq 2^{\circ}C$			
	-8° to $-15^{\circ}C$	$\leq 3^{\circ}C$			
	Areas with vigorous cu build-ups due to surface heating			Light	90%

* Icing intensity is defined in terms of its effect upon a reciprocating engine, straight-wing transport aircraft (C-54, C-118). The pilot must refer to the aircraft "dash-one" for recommended actions.

Table 4-2 (cont'd)

(No Upper Air Data Available - Rules 3-9)

Rule	Description	Position of clouds	Icing Forecast
3	Not due to frontal activity or orographic lifting	Over areas with steady liquid precipitation	Little or none
		Over areas with no liquid precipitation	Light
4	Due to frontal activity or orographic lifting	Presence/absence of precipitation not an indicator	Indeterminate
5	Up to 300 miles ahead of warm frontal surface position		Light
6	Up to 100 miles behind cold frontal surface position		Moderate
7	Over deep, almost vertical low pressure center		Moderate
8	In freezing drizzle (in or below clouds)		Moderate
9	In freezing rain (in or below clouds)		Severe

Icing Type Forecasts

Rule	Temperature	At or in	Icing type forecast
10	Below -15°C	Flight altitude	Rime
	-1° to -15°C	Stable stratiform clouds	
11	0° to -8°C	Cumuliform clouds and freezing precipitation	Clear
12	-9° to -15°C	Unstable clouds	Mixed (rime and clear)

temperature and dewpoint depression profiles; icing is indicated by a multiplicative value of the dewpoint depression that is higher than the air temperature, while the intensity of the icing is suggested by the size of the area between the two curves. This method borrows heavily from the concepts outlined in the Appleman procedure, being based primarily on considerations of cloud saturation with respect to water and ice.

A final method is suggested where data are extremely limited (i.e. no cloud or flight level temperature information). Figures giving the probable frequency of icing as a function of altitude and season are utilized based on climatological considerations of temperature and cloudiness. Alternatively, information on the climatological frequency of cloud cover and temperature along a given route are utilized to derive the percentage of icing clouds as a function of temperature. The product of the icing cloud frequency for a given temperature times the climatological frequency of cloud yields an estimate of icing probability. These methods have been utilized primarily for planning and design purposes rather than the forecasting of icing under individual circumstances.

Bocchieri (1980)

In this study, a statistical regression analysis was performed on a series of predictors to identify those variables important to the specification of precipitation type. It was determined that the mean temperature in the surface to 1 km layer and 500 m to 2.5 km layer, the depth and area of the warm layer (defined by the profile of temperature relative to $0^{o}C$), and the depth and area of the surface-based cold layer (with respect to the dewpoint profile) were important. The results indicated that the discrimination ability of the system with respect to freezing rain was marginal, correctly specifying occurrence on the order of 50% of the time. Freezing drizzle, which occurred in 44% of the soundings with no warm layer present, accounted for much of

the difficulty; in those instances, the regression equations specified a high probability of frozen rather than freezing precipitation. Thus, additional predictors were required that could discriminate between freezing and frozen precipitation conditions in the absence of a warm layer.

Keeter and Green (1981)

This work centred on the construction of a scheme designed to predict the predominance of frozen precipitation given the occurrence of precipitation. In this methodology, frozen precipitation included snow and/or sleet while unfrozen precipitation consisted of any combination of rain, drizzle or freezing precipitation. Mixed cases were considered to be frozen if measurable amounts of frozen precipitation occurred. A linear multiple regression equation utilizing the 1000 to 700 mb thickness and the 850 mb temperature was constructed for Charlotte, North Carolina. The equation was of the form:

$$P = a + b\Delta Z + c\,T_{850}$$

where P = conditional probability of the predominance of frozen precipitation

ΔZ = 1000 mb to 700 mb thickness

T_{850} = 850 mb temperature

The scheme was found to have good success in predicting the occurrence of non-freezing precipitation but generally less success in the prediction of freezing precipitation. The study results suggested that thickness, 850 mb temperature, surface temperature and surface dewpoint were all likely indicators of precipitation phase. For the purposes of

the climatological assessment of icing, the importance of this work lies in its effort to identify those variables that indicate supercooled water content within clouds.

Ervik and Fikke (1984)

This model is similar in approach to the Lawford (1971) and Jensen (1963) procedures, although the work was directed towards the icing of transmission lines due to precipitation and in-cloud processes. The model uses Chaine (1974) as a basis, although it has been extended to include precipitation and data from a variety of station locations. Figure 4-7 shows the program logic. A modified from of this logic, which could be applied to aircraft icing, would involve measures of atmospheric stability and moisture content to broadly indicate type and severity of ice accretions. Critical values at the decision points would be obtained through analysis of actual icing data. As with the other descriptive models, the impact of cloud morphology and position within the cloud could only be grossly represented, and aircraft-dependent effects would be ignored.

Huffman and Norman (1985)

A more direct approach to the problem of specifying the occurrence of freezing precipitation (and consequently supercooled liquid water) was contained in this paper which is an extension of Bocchieri (1980). The procedure involved the construction of a decision tree (Figure 4-8) based on physical principles with indentified predictors that governed the decision points along the path. Atmospheric variables utilized included the cloud top temperature (T_c) and depth (Δp) of the cloud layer to specify the phase of the nascent hydrometeors, the presence of a warm layer measured by its depth (WD), area (WA, indicated by the region between 0^oC and the temperature profile) and top level (WT), the presence of an underlying cold layer measured by its depth (CD) and area (CA), the surface temperature (T_{sfc}) and the dewpoint temperature

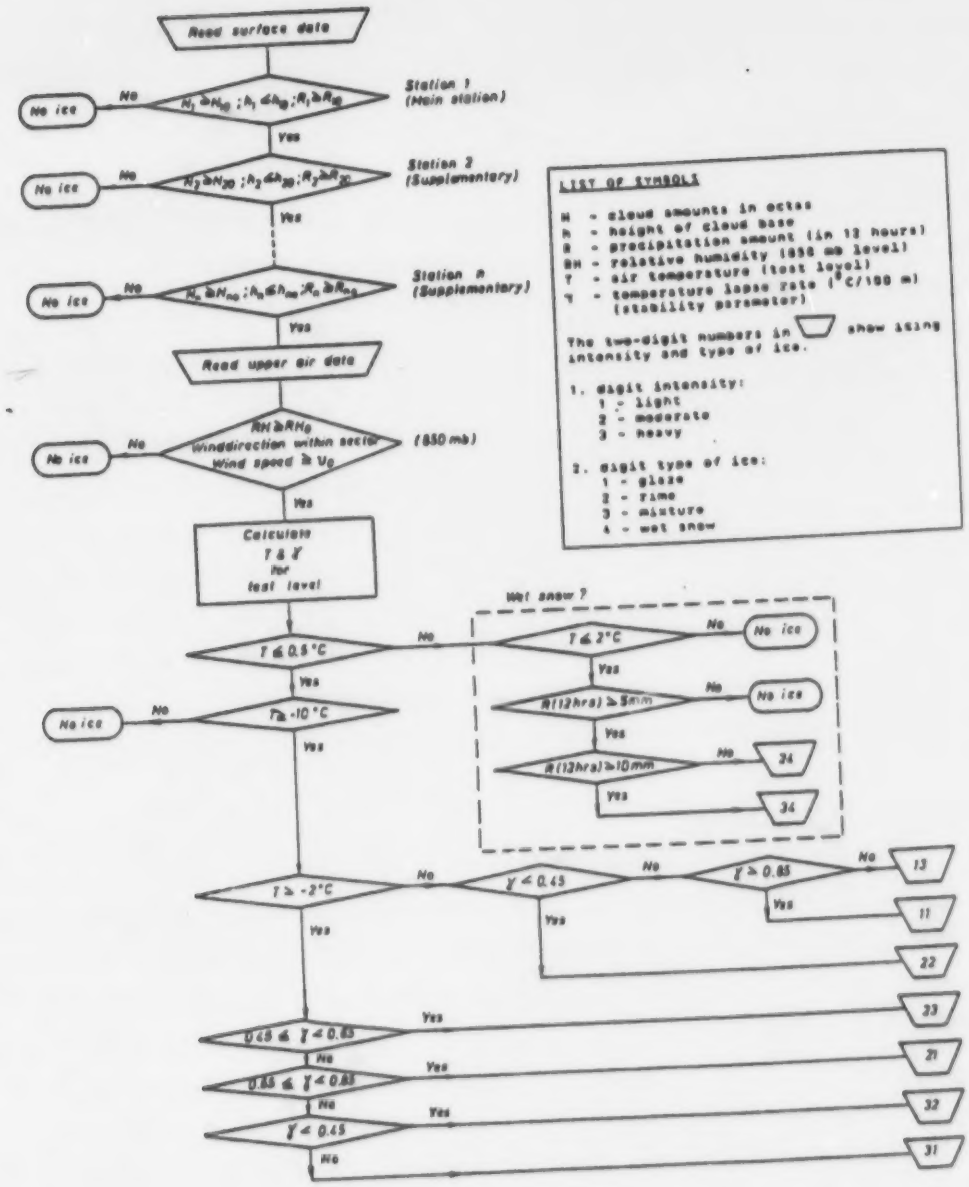
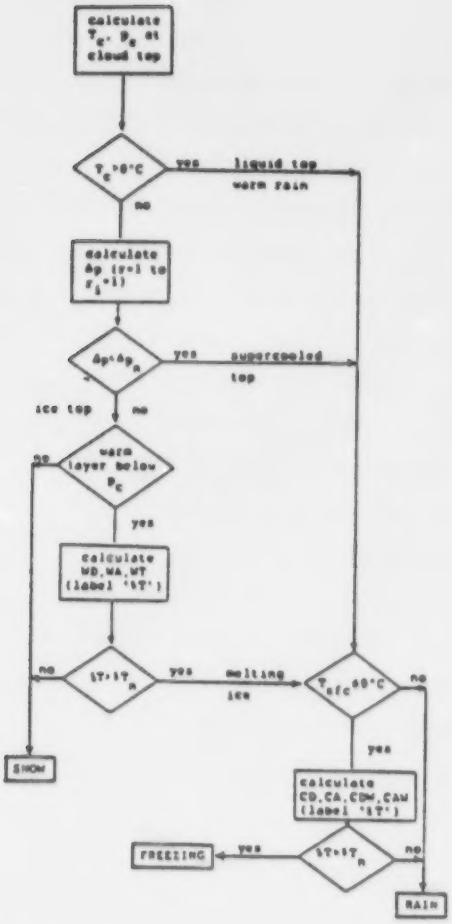


Figure 4-7: Ice accretion logic (Ervik and Fikke, 1984).



Decision tree describing the physical pathways which lead to liquid, freezing, and frozen precipitation.

Predictor	Threshold[1]	Default Values
T_c & Δp	T_c < -10.0°C or (T_c ≤ 0.0°C and Δp > 20.0 mb)	Liquid top
WA	≥ 30.0°C m	0[2]
WD	≥ 350.0 m	0[2]
WT	≥ 400.0 m	0[2]
CD	≥ 300.0 m	0[4]
CDW[3]	≥ 300.0 m	0[4]
CA	≥ 50.0 m	0[4]
CAW[3]	≥ 50.0 m	0[4]
T_{sfc}	< 0.0°C	
TW_{sfc}[3]	< 0.0°C	

1. A binary value of 1 is assigned if the threshold is met; otherwise it is set to 0.
2. In the absence of a warm layer beneath the cloud top or when a liquid cloud top phase is estimated.
3. Calculated with respect to wet-bulb temperature.
4. In the absence of a warm layer aloft.

Figure 4-8: Precipitation phase decision tree (Huffman and Norman, 1985).

profile (to measure the effect of evaporative cooling of droplets within the cold layer).

The validity of the decision tree/decision point structure was tested by discretizing the raw predictors into binary values based upon threshold values. A stepwise screening regression was performed on each of the combination predictors that formed the physical pathways of the decision tree. The regression equations were then independently verified against precipitation type data. It was found that the system tended to under-specify freezing conditions by 16%; freezing conditions occurred when forecast roughly 50% of the time. The relevance of this work to the study objectives resides in the quantitative assessment of the relative importance of various physical processes in the generation of freezing precipitation, and the construction of physically motivated pathways for the production of supercooled liquid water. In particular, the study defined a new process involved in the production of freezing precipitation in the absence of a warm layer, a weakness in the theory identified by Bocchieri (1980). A decision tree incorporating some of these concepts might prove useful in the specification of an aircraft icing algorithm.

Guttman and Jeck (1987)

In this work, 23 soundings of temperature and humidity in the Washington, D.C. area were examined to deduce the distribution of clouds and icing conditions when low ceilings occurred with surface temperatures near freezing. With this information, the AWS icing forecast procedure was used to produce predictions of the icing probability, type and severity. These forecasts were verified with pilot reports; given the problems associated with verification by spot information, the results were considered to be satisfactory. Effects of local topography were found to be important on the height of cold, low ceilings, particularly with regard to local moisture sources. In terms of the present study, this work is important in that it

represents a reasonably successful attempt at implementing and verifying the AWS forecast scheme. An important result of the analysis was the existence of an inversion or isothermal layer aloft that in many cases significantly mitigated the icing conditions, despite the presence of deep and apparently continuous cloud above the ceiling height. It seems clear from this result that any scheme that is implemented must in some fashion account for the variation of stability above the surface level.

5. CLIMATOLOGICAL AIRCRAFT ICING PREDICTION

The following sections describe the data available for the climatological prediction of aircraft icing, the procedures followed to determine the list of candidate models from the selections reviewed in Section 4 and the details of the model implementation strategy.

5.1 Data Sources

At AES, three data sources are archived that contain information suitable for east coast climatological ice accretion modelling. These are: the Naval Environmental Data Network (NEDN) archive, Ocean Weather Station (OWS) data, and selected coastal station data. Each of these sources contains the necessary minimum requirement, upper air measurements of temperature and moisture. The relative advantages and limitations of these data are discussed in turn below.

The NEDN data represent a blend of numerical objective analyses and prognoses resulting from a mix of man-machine products. The data are gridded on the Fleet Numerical Oceanography Center (FNOC) 63 x 63 grid. This grid results in the most complete coverage of the offshore environment obtainable from the three difference sources (Figure 5-1). Temperature and dewpoint depression data are contained in the Canadian Digital Archive (CDA) in MAST 2 format for the following pressure levels: surface, 1000 mb, 925 mb, 850 mb, 700 mb, and 500 mb. An evaluation of these data relative to reported radiosonde and aircraft observations has been conducted (Kel Research, 1985). Agreement was generally excellent up to the 500 mb level, although there was a noticeable decay with increasing altitude above the 850 mb level.

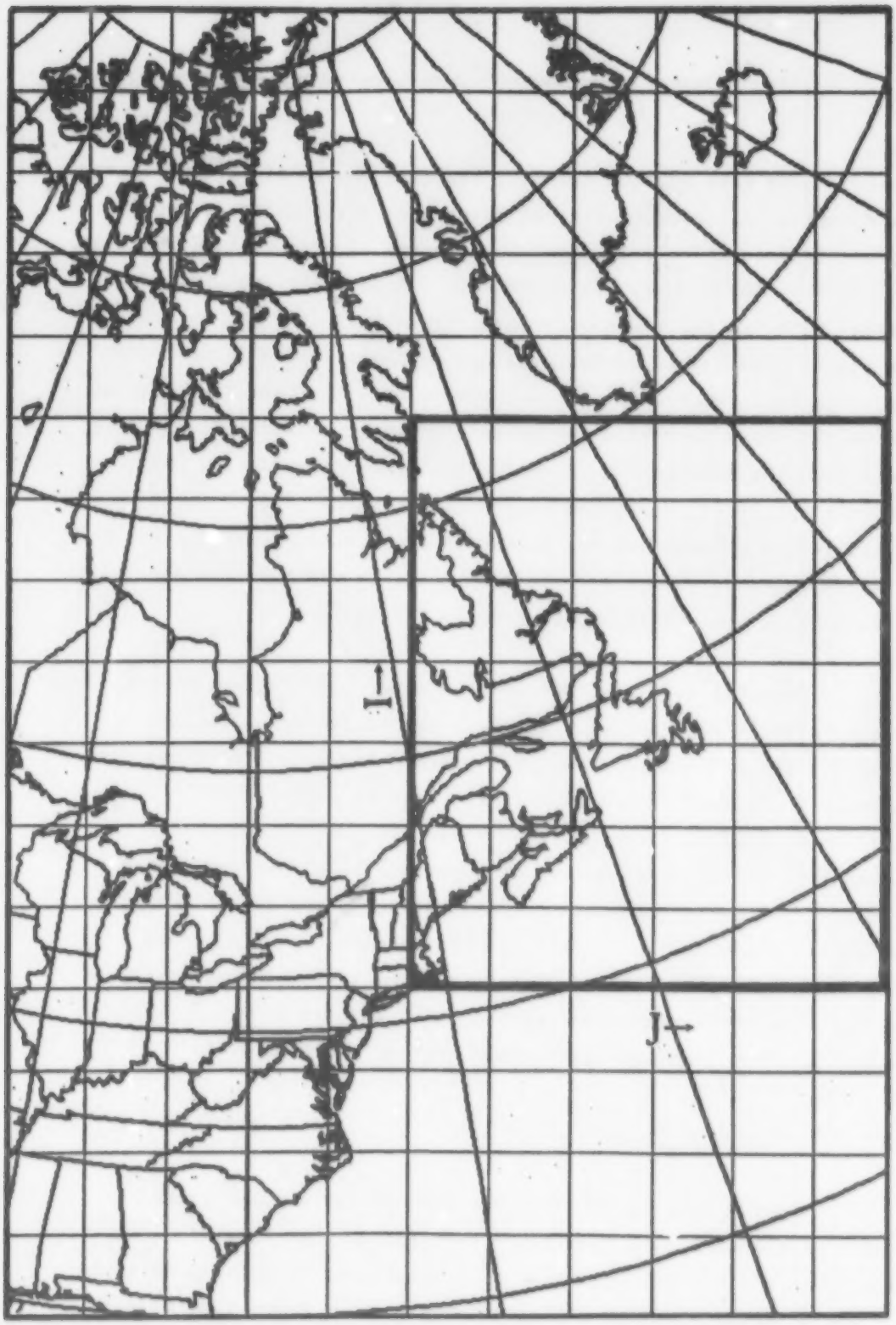


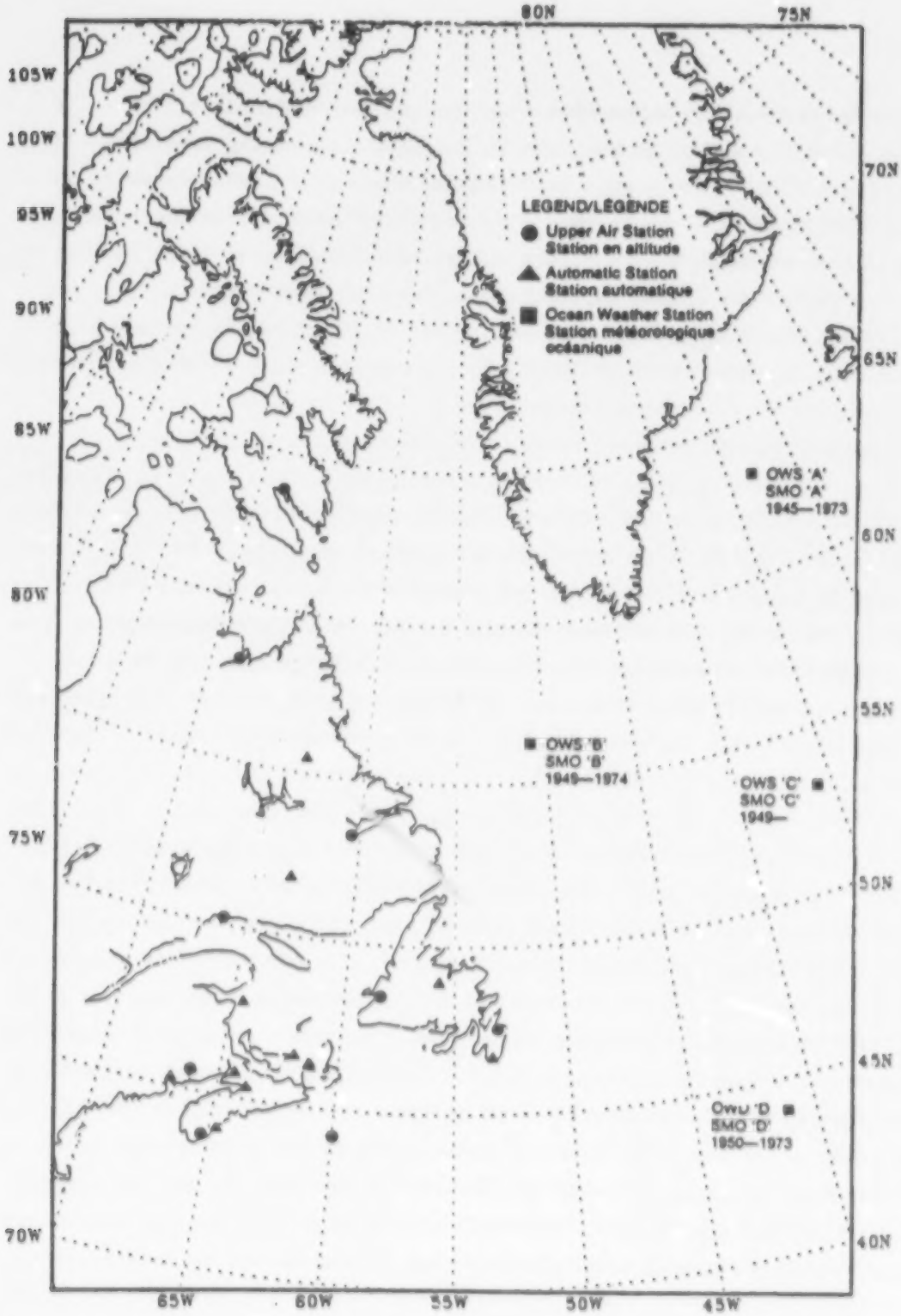
Figure 5-1: Proposed NEDN grid (I= 17 to 24, J= 33 to 39) for climatological ice accretion modelling for the Canadian East Coast.

OWS data provide the most reliable source of data offshore. The data are collected by trained observers, instruments are well-sited and maintained, and a full observing program is conducted (Mortsch et. al., 1985). The primary limitations to OWS data are twofold: poor spatial coverage and end-of-service (Figure 5-2). As can be seen from the figure, the number of weatherships offshore Canada is small, and these are well removed from the coastal zone. The fact that most of the weatherships have been decommissioned is of secondary importance, since from the perspective of an ice accretion climatology, the relevant factor is the length of the observing record. However, a system set up to hindcast ice accretion might also be useful from a forecast guidance viewpoint. In that case, it might be preferrable to implement a system based upon currently available data.

Coastal stations that conduct upper air programs (Figure 5-2) provide a third alternative. The data are collected by trained observers under WMO standards. The primary limitation of these data relates to the differences between the coastal and offshore environments. Significant local effects produced by land-sea temperature differences, uplift of onshore flow across the coastal boundary, and surface roughness characteristics can all effect parameters important to the physics of ice accretion. A second limitation relates to the small number of coastal upper-air stations. This problem could be reduced by combining the OWS and land station data to provide coverage approaching that of the NEDN grid.

5.2 Candidate Models

The procedure followed was essentially a multi-stage screening process. The models are required to meet specific criteria related to the overall objective of producing an acceptably reliable and useful climatology of aviation icing: model input requirements, the appropriateness of model output and the efficiency of data processing. Within this content, it should be understood that the



Canadian East Coast Locations of Upper Air, Automatic and Ocean Weather Stations
Localisations sur la côte Est du Canada des stations météorologiques en altitude, automatiques et océaniques

Figure 5-2 Source: Swail and Mortsch (1984)

screening is necessarily subjective: the models are not perfect, nor are they perfectly suited to the task at hand. The screening process, if strictly applied, can be used to determine whether any of the models in their published form can be used as stand-alone tools for the climatological assessment of aircraft icing; however, some of the models may not be sufficient by themselves, but may provide useful insights into the accretion process, and could be beneficially applied in conjunction with other procedures. Thus, modified forms of the models may provide attractive alternatives in order to attain the overall modelling objective.

Direct examples of this are those models that produce information on drag and lift performance degradation; these models do not uniformly supply the required basic icing information, but might be applied to the problem of differentiating between severity of icing for different aircraft types under the same environmental conditions. At that stage, those models that produce quantitative information regarding icing intensity would be required in order to apply those procedures.

Since some measure of liquid water content and droplet size is required in any numerical simulation of ice accretion (e.g. the AWS/USAF method uses the cloud model of Best, 1952 to supply liquid water content values for assumed droplet sizes), it is necessary to consider the possibility of extrapolating this information from the available data for quantitative models. Thus, two model groups are indicated: quantitative and descriptive. The descriptive models are more limited in scope, but require less peripheral information. However, it is not clear that this is necessarily an advantage since generalizations of icing severity that cannot account for fairly significant differences in environmental conditions and aircraft characteristics may not be providing any real information.

A critical but perhaps even more subjective criteria relates to the magnitude of computational effort required to produce typical icing climatologies. Since to a large extent, measures of model efficiency are not part of the literature, this criteria must be stated in general terms: the model must be capable of completing a full climatological assessment (several years of data) on a 3 dimensional grid of the Canadian East Coast (e.g. NEDN domain, Figure 5-1 or Ocean Weather Ship Data, Figure 5-2) with reasonable turn-around.

Based on these criteria, four groups were established representing quantitative and descriptive models of helicopter and airframe icing. The conceptual outline of these groups is presented in Figure 5-3. The quantitative airframe model group will produce an icing equivalence on a cylinder as discussed by Newton (1978). A post-processor step will allow the stratification of the sample according to a particular aircraft type, if so desired, incorporating the impact of the standard icing condition on that particular aircraft's flight performance. In order to accomplish this, it will be necessary to transfer the equivalent cylinder icing rate to some measure of icing on an airfoil (e.g. icing thickness and extent). This might best be accomplished through the use of a look-up table within the post-processor. Thus, given the equivalent cyclinder icing rate and the flight parameters (p,T,V and airfoil characteristics) a measure of icing extent from the leading edge of the wing and ice thickness could be found. This table could be produced by running one of the more sophisticated ice accretion models (including potential flow code to simulate the flow around the airfoil) beforehand, taking into account the various parameter combinations. The descriptive aircraft model(s) will produce generalized icing severity class and type. The quantitative helicopter model group will produce estimates of icing occurrence and extent. The descriptive models will be restricted to the assessment of occurrence or non-occurrence of icing conditions. Table 5-1 presents the list of the candidate models selected through the screening process.

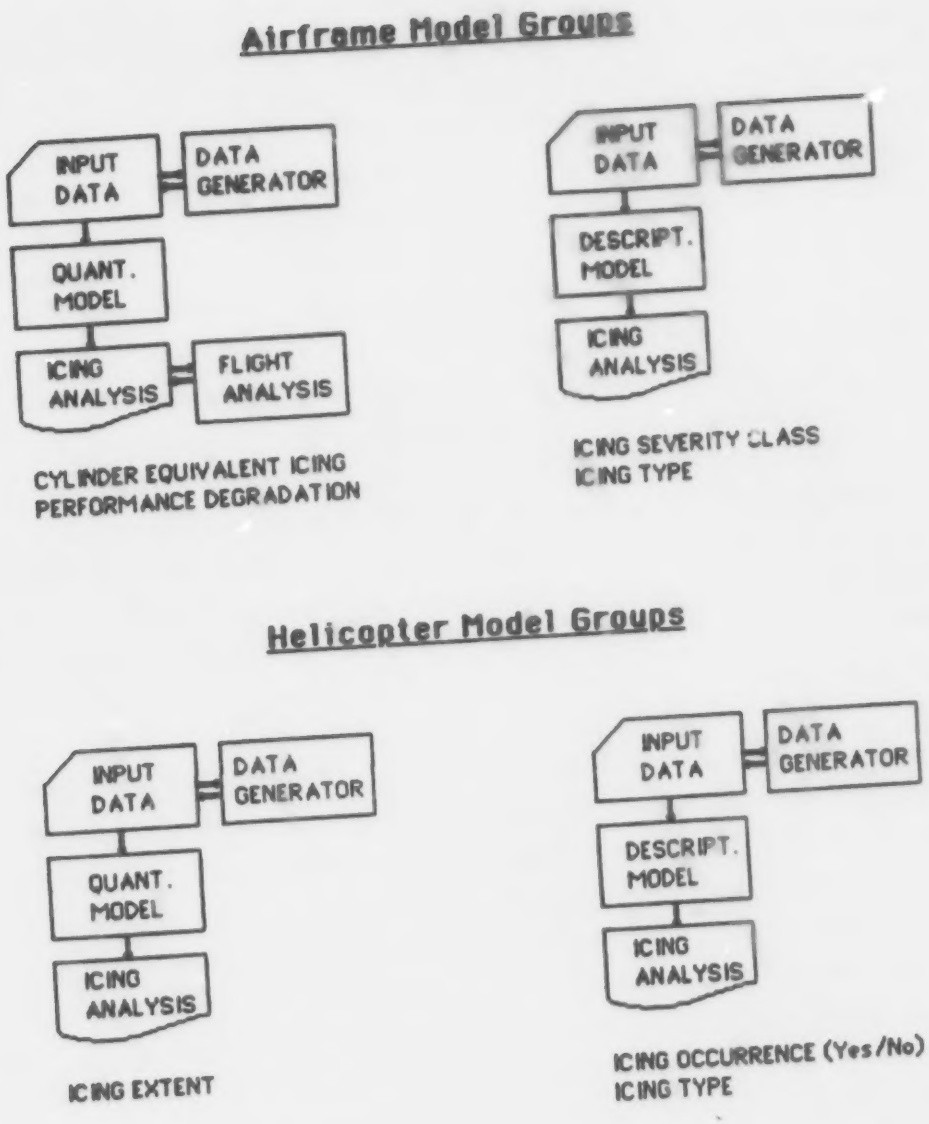


Figure 5-3: Conceptual outline of airframe and helicopter model groups.

Table 5-1

Candidate Models

AIRFRAME MODELS

QUANTITATIVE

AWS/USAF (1980) - 1 with Best (1952) LWC, drop-size or adiabatic LWC

MAKKONEN (1984) with Best (1952) LWC, drop-size or adiabatic LWC

DESCRIPTIVE

JENSEN (1963)/LAWFORD (1971)/Ervik and Fikke (1984)

AWS/USAF (1980) - 3

HUFFMAN AND NORMAN (1985)/NWS

HELICOPTOR MODELS

QUANTITATIVE

FLEMMING AND LEDNICER (1986) with Best (1952) LWC, drop-size or adiabatic LWC

DESCRIPTIVE

JENSON (1963)/LAWFORD (1971)/Ervik and Fikke (1984)

AWS/USAF (1980) - 3

HUFFMANN AND NORMAN (1985)/NWS

The AWS/USAF (1980) procedures have been evaluated in a variety of situations. Perhaps the most deliberate verification of those procedures was reported by Cohen (1983). The sounding method (AWS/USAF-1) and the rule-based method (AWS/USAF-3) were evaluated based on a series of flights into areas in which icing was forecast. Both methods tended to work well in predicting the occurrence of icing but were biased towards more severe icing than was actually observed, particularly in the case of observed light icing (the most commonly experienced category). The methods were not exceptional in their capacity to predict the type of icing either, although part of the problem may have been related to the difficulty in spotting and identifying clear ice on the aircraft extremities. Certainly, the lack of the ability in the procedures to account for the speed of the aircraft in relation to the drop size, liquid water content and temperature of the cloud would effect the accuracy of the result. Operational forecasts based essentially on the AWS/USAF techniques have shown notable agreement in a general sense with observed icing conditions (Craig, 1988, personal communication) for helicopters on the Canadian east coast. However, comparisons of observed ice accretion versus that predicted using these techniques suggests that their utility resides in determining the occurrence or non-occurrence of icing rather than quantitative amounts. The other candidate models have not been verified in terms of the aviation icing problem; this step will be essential in determining the utility of these procedures. However, it seems likely given the the inherent complexities of icing on fixed-wing and rotary aircraft that reliable quantitative forecasts of ice accretion may be difficult to achieve using any of these techniques.

5.3 Model Implementation Strategy

This section is concerned with outlining a strategy for the design and implementation of the climatological aircraft icing system. Flow charts outlining the logic of each of the identified candidate models are presented in Figures 5-4 to 5-9. Two types of input data are assumed: the NEDN grid point data and simultaneous surface and upper air data from weathership archives and/or coastal stations. Since the NEDN data does not contain routine surface observations (present weather, cloud level, cloud type), additional options have been provided to generate the required data from available sources (Figures 5-10 to 5-11): in particular, quantitative information on liquid water content is estimated from Best (1952), or from reference to empirical measures of adiabatic liquid water content as a function of position within the cloud. The cloud type can be derived by referring to the thermal profile: unstable profiles promote convective development while stable profiles promote layer type cloudiness. However, these data generation techniques need to be tested against observational data to establish their validity. The design strategy of the overall system is outlined in Figure 5-12. The input data are fed into the icing model which incorporates the necessary routines for data generation: the model then produces aircraft icing information in the standard TDF1129 format for manipulation using the climatological information system packages (MAST, DUST, CONAN). Output would include the data shown in Table 5-2. This file could then (optionally) be sent to the post-processor
(Table 5-3) to estimate the impact of the ice accretion on flight conditions: thrust increase required over clean aircraft operation to maintain flight safety given a standard icing exposure interval and the maximum icing exposure time. The TDF1129 file, with or without the degradation analysis data, could be input into MAST/DUST for manipulation; by reconfiguring the data file (slotting the desired variable into a standard position), these data could also be plotted via CONAN.

AWS/USAF(1980) - 1

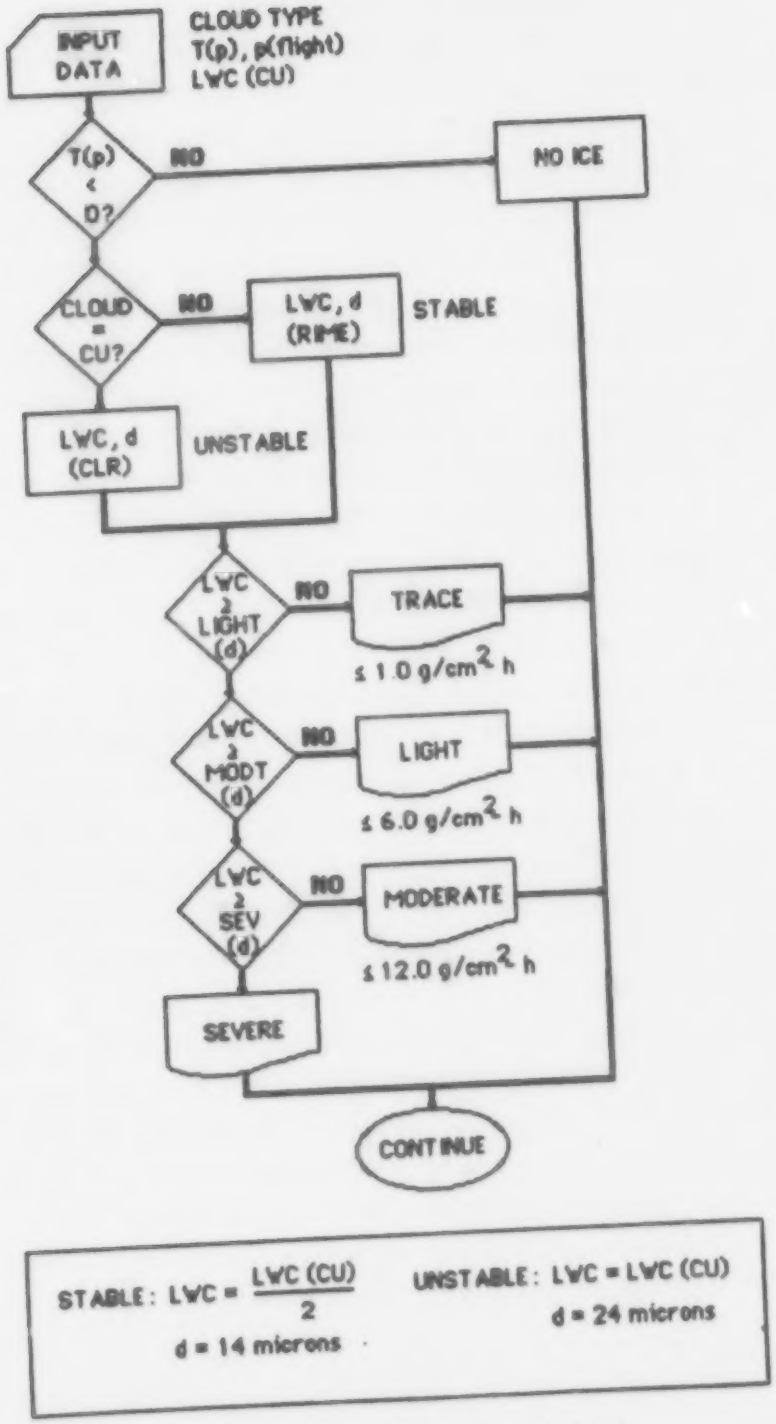


Figure 5-4: Modified AWS/USAF (1980)-1 model logic.

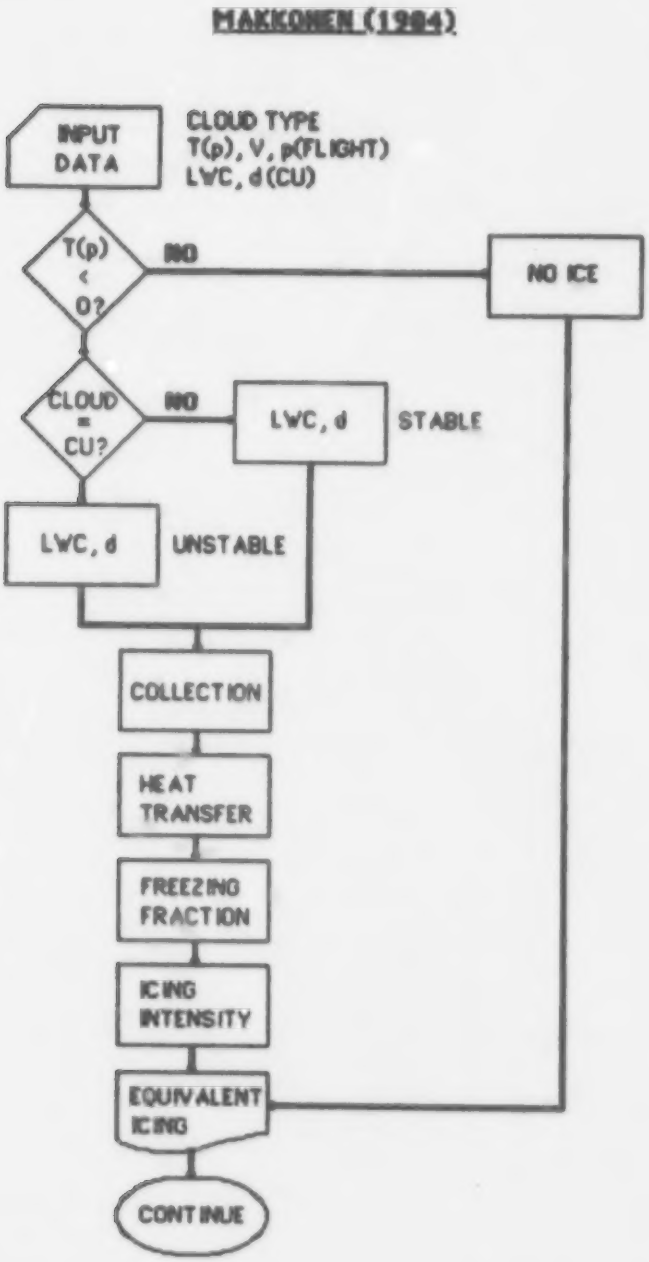


Figure 5-5: Modified Makkonen (1984) model logic.

LAWFORD (1971)

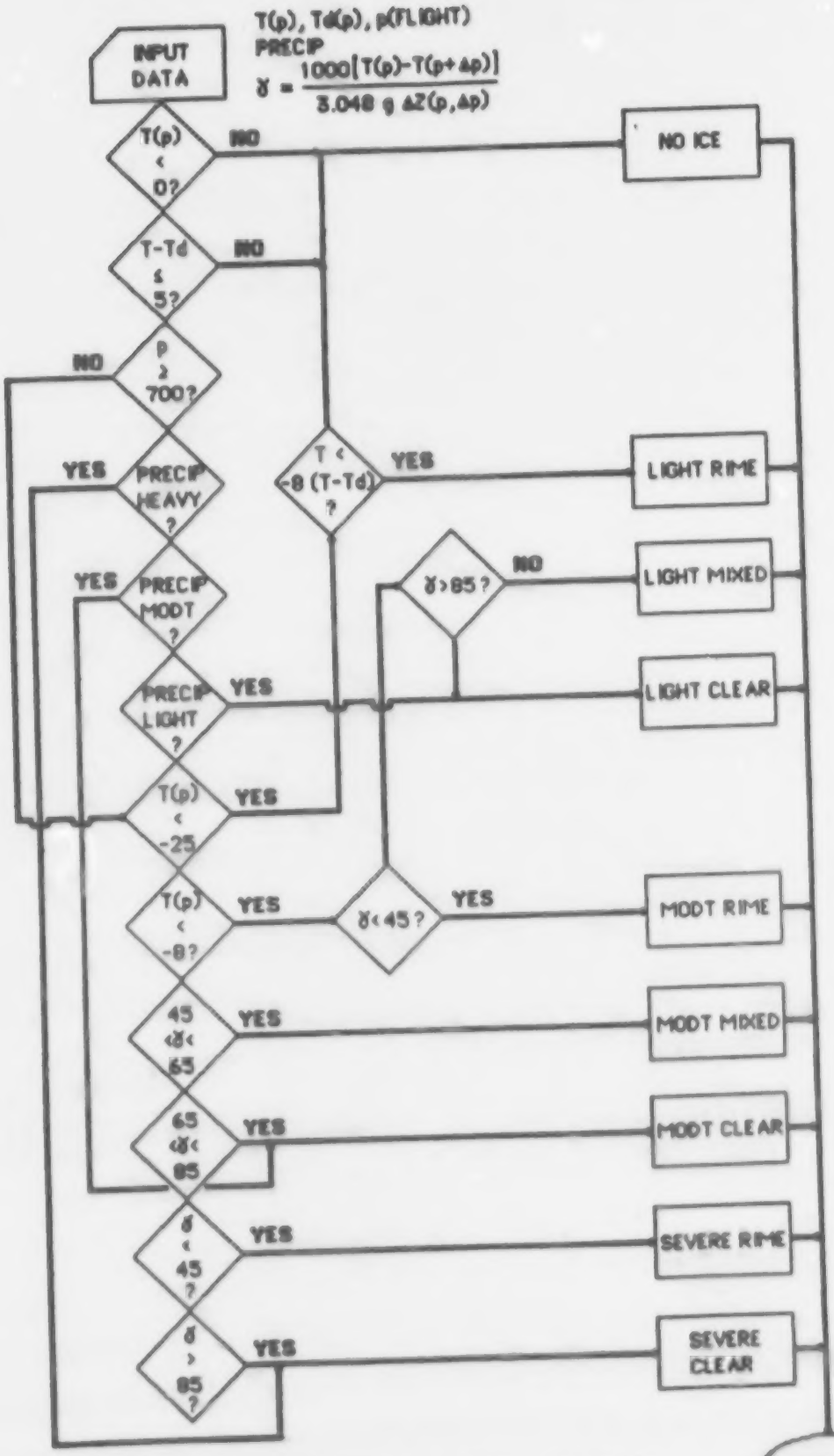


Figure 5-6: Modified Lawford (1971) model logic.

AWS/USAF (1980) - 3

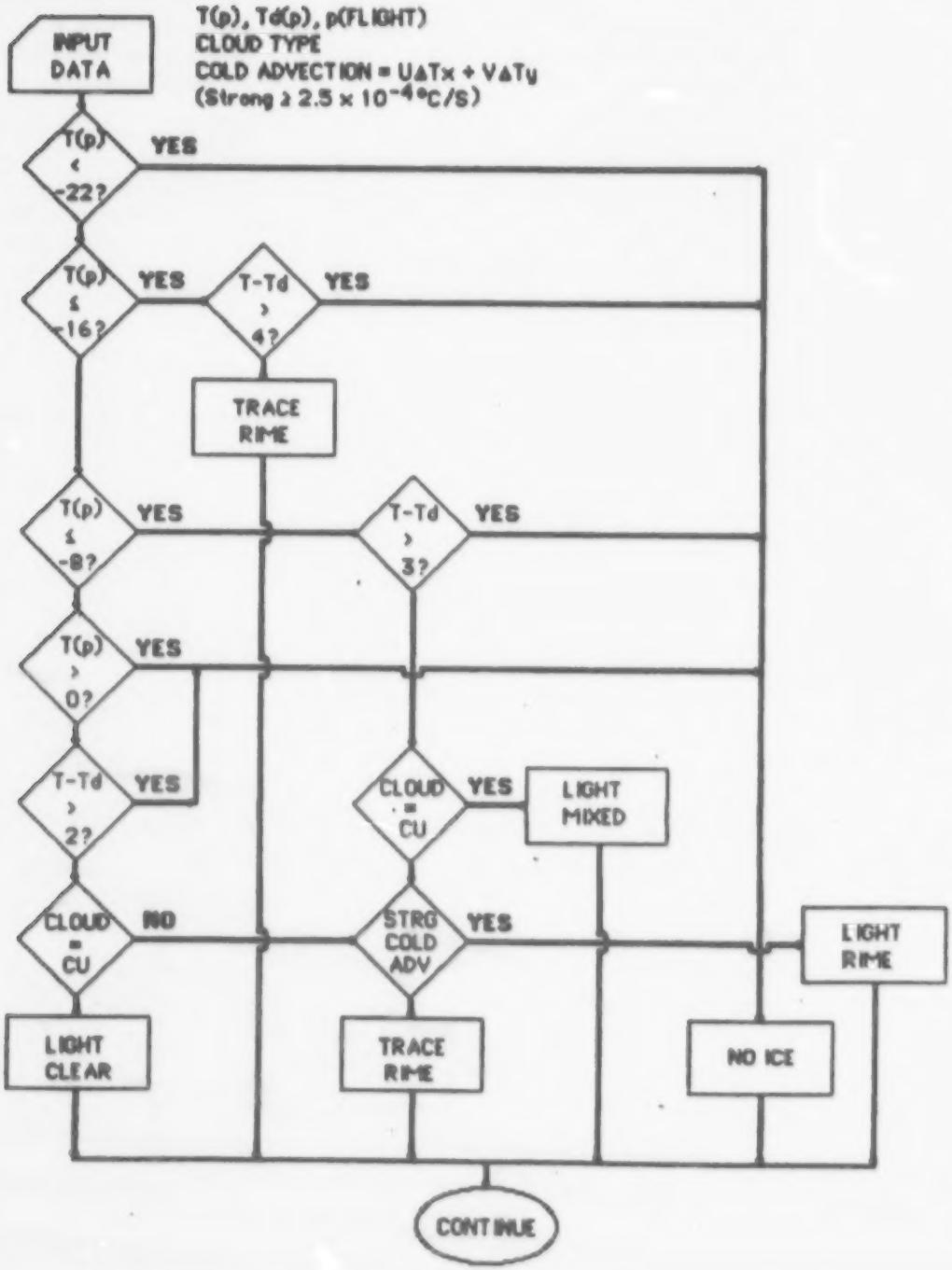


Figure 5-7: Modified AWS/USAF (1980)-3 model logic.

HUFFMAN AND NORMAN (1985)

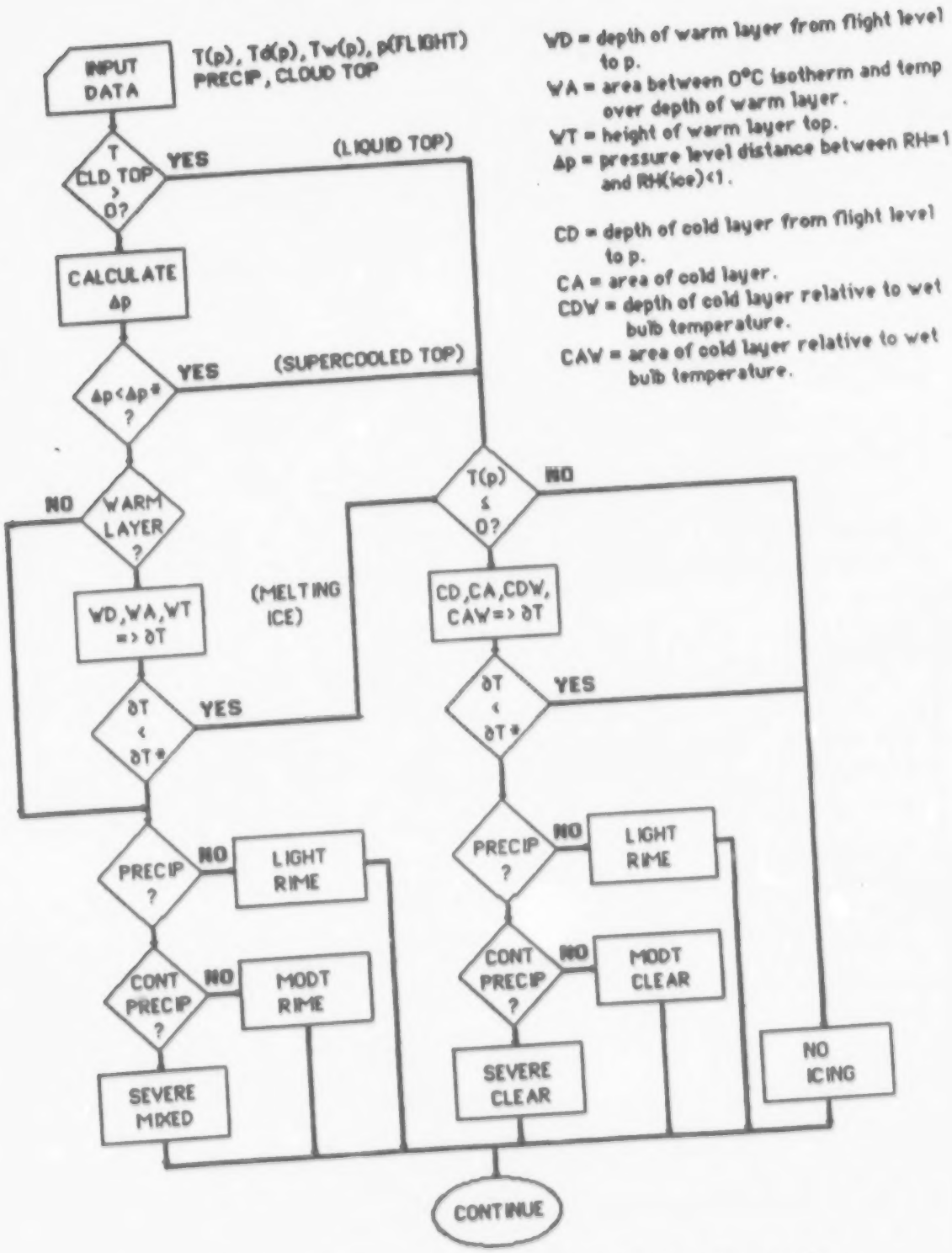
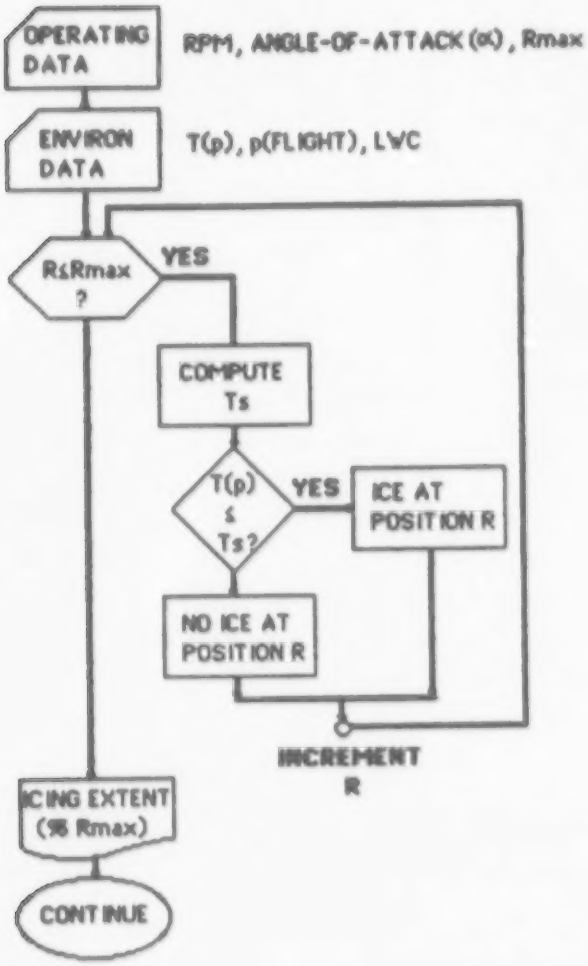


Figure 5-8: Modified Huffman and Norman (1985) model logic.

Flemming and Lednicer (1986)



$$Ts = \frac{273.15 - .33(\alpha - 6)}{1 + \frac{\gamma - 1}{2} r M^2}$$

$$r = .0944\, M\, LWC^2 + .385\, M\, LWC + .98\, M^3 - 1.33\, M - .0283\, LWC^2 - .115\, LWC + 1.077$$

$\gamma = Cp/Cv$

M = Blade Position Mach Number

Figure 5-9: Modified Flemming and Lednicer (1986) model logic.

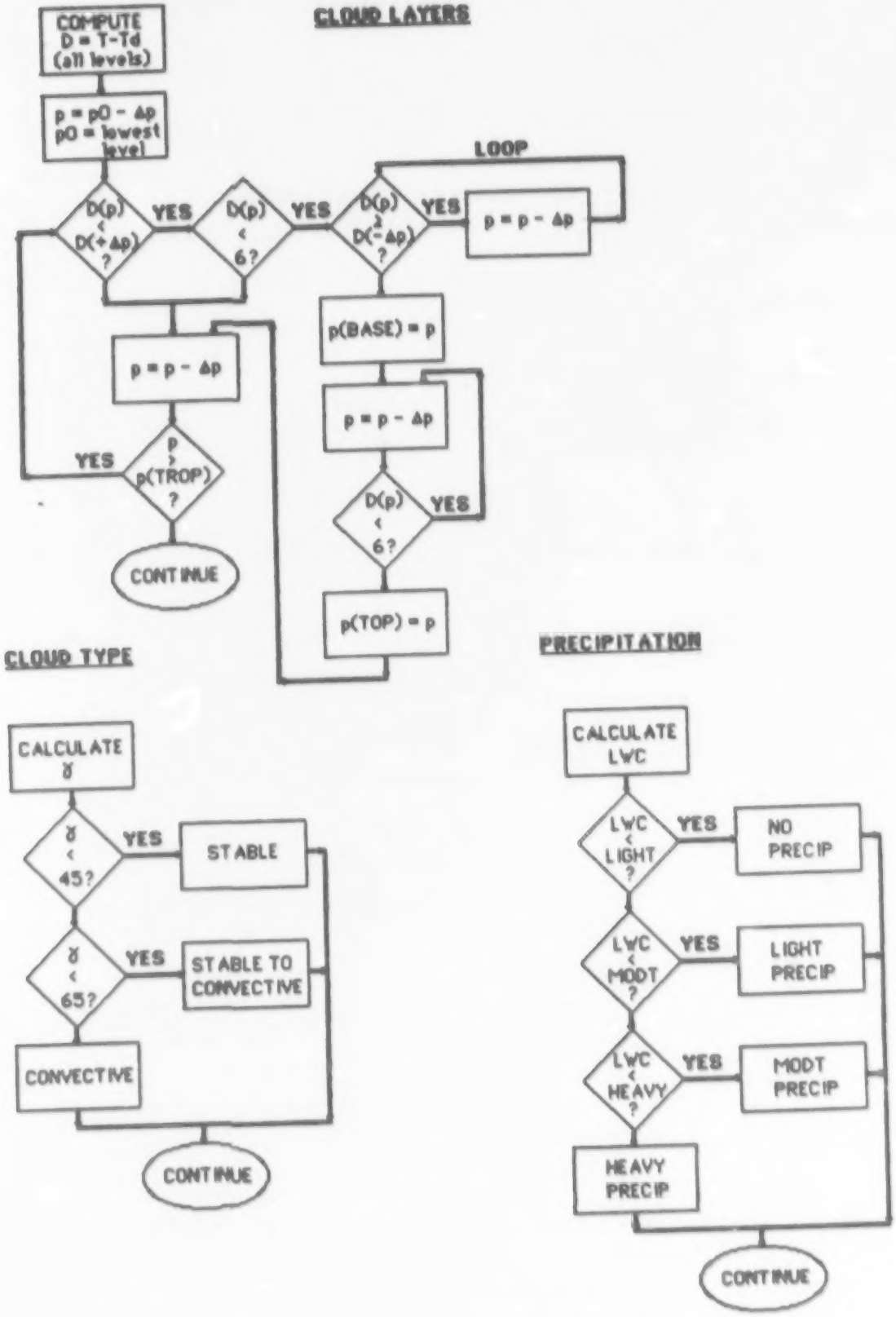
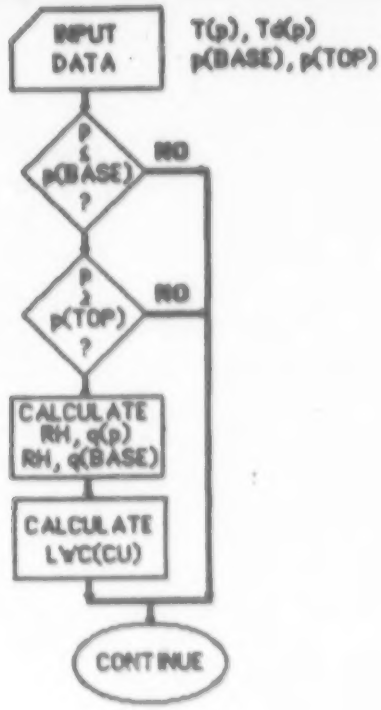


Figure 5-10: Cloud and precipitation data generation logic.

BEST (1952)

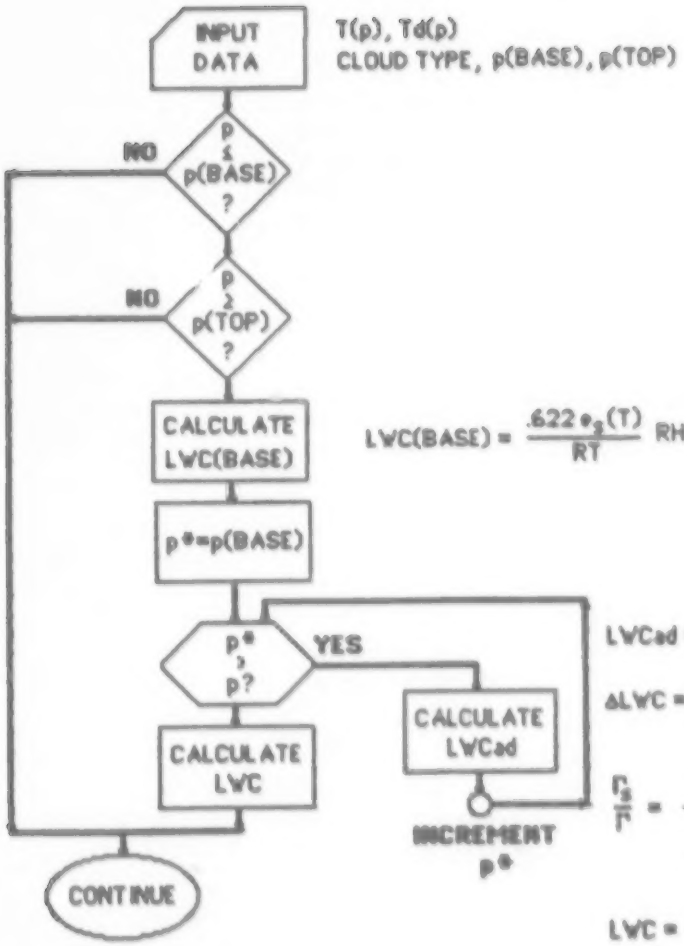


$$RH(p) = \exp\left[\left(1-\frac{T}{Td}\right)\frac{Lv}{RT}\right]$$

$$q(p) = \frac{.622\, e_s(T)\, RH}{p}$$

$$LWC(CU) = \frac{[q(BASE) - q(p)]\, p}{2.87\, T(p)} \quad g/m^3$$

ADIABATIC



$$LWC(BASE) = \frac{.622\, e_s(T)}{RT}\, RH$$

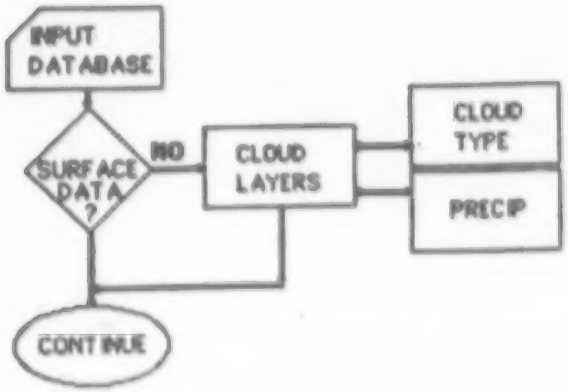
$$LWCad = LWC(BASE) + \sum \Delta LWC$$

$$\Delta LWC = \left\{\frac{LWC(+\Delta p)}{p}\left[1-k\frac{\Gamma_s}{\Gamma}\right] - \frac{1}{L}\left[1-\frac{\Gamma_s}{\Gamma}\right]\right\}\Delta p$$

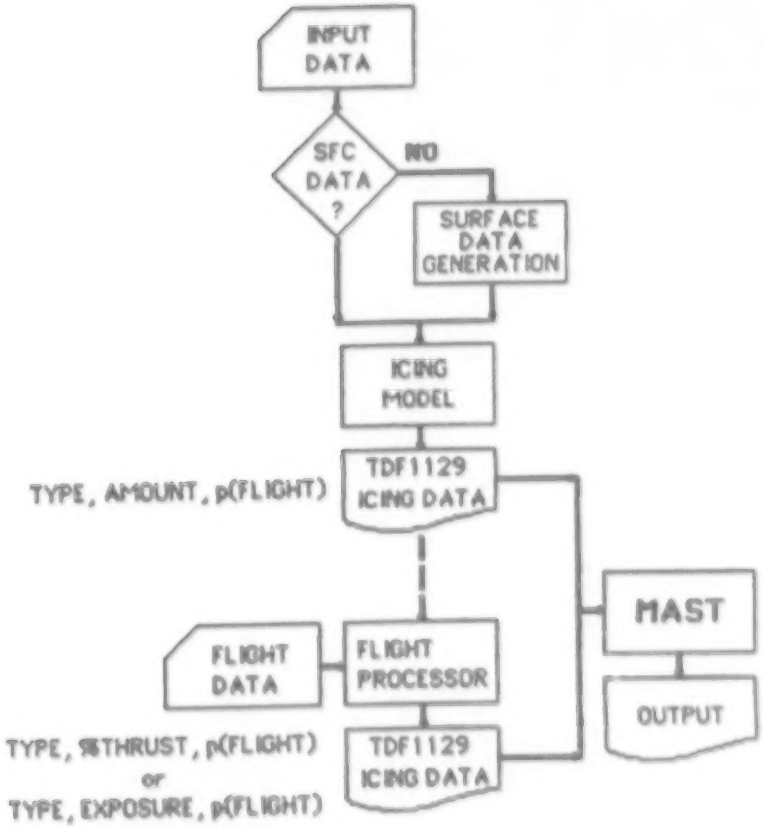
$$\frac{\Gamma_s}{\Gamma} = \frac{1+\frac{Lq_s}{RT}}{1+\frac{.622\,L^2 q_s}{C_p RT^2}}$$

$$LWC = LWCad \cdot f\{(CLOUD\ TYPE,\ p/p(BASE))\}$$

Figure 5-11: Liquid water content data generation logic.



a



b

Figure 5-12: Icing model design strategy for (a) surface data generation and (b) overall model implementation.

Table 5-2
TDF1129 Format - Aircraft Icing

Tape Field Number	Tape Position	Element	Units/Code
001	01-03	Source Deck Number	
002	04-06	Marsden 10° Square	
003	07-08	Marsden 1° Sub-Square	
004	09	Quadrant	Code A
005	10-12	Latitude	10th's of degrees
006	13-16	Longitude	10th's of degrees
007	17-20	Year	
008	21-22	Month	
009	23-24	Day	
010	25-26	Hour-GMT	
011	27		
011	28-29		
012	30	Air Speed Indicator	Indicator B
012	31-33	Air Speed	Knots
012	34		
013	35-36		
014	37-38	Present Weather	Code D
015	39	Past Weather	Code E
015	40-44	Pressure Level	10th's of mb
017	45	Temperatures Indicator	Indicator D
017	46-49	Air Temperature	10th's of degrees C
018	50-53		
019	54-57	Dew Point Temperature	10th's of degrees C
020	58-61		
021	62	Total Cloud Amount	Oktas
021	63	Lower or Middle Cloud Amount	Code F
021	64	Type of Low Cloud	Code G
021	65	Cloud Height Indicator	Indicator E
021	66	Lowest Cloud Height	Code H
021	67	Type of Middle Cloud	Code I
021	68	Type of High Cloud	Code J
022	69-70		
023	71		
024	72-73		
025	74-75		
026	76		
027	77-78		
028	79-80	Country Code	Code N
029	81		
030	82		
031	83		
032	84-86	Thrust Increase	Percent
033	87	Type of Ice Accretion	(1-NO ICE,2-RIME, 3-MIXED, 4-GLAZE)
034	88-89	Thickness of ice per 30 min.	millimeters
035	90		

Table 5-2 (cont'd)

TDF1129 Format - Aircraft Icing

Tape Field Number	Tape Position	Element	Units/Code
036	91-97		
037	98		
038	99		
039	100		
040	101-102	Maximum Icing Exposure Time	Minutes
041	103-104		
042	105		
042	106		
042	107		
042	108		
042	109		
043	110-111		
043	112-113		
044	114		
045	115		
046	116-117		
047	118		
048	119-120		
049	121-122		
050	123-124		
051	125	Ship Position	- Flag
052	126	Wind	- Flag
052	127	Visibility	- Flag
052	128	Present Weather	- Flag
052	129	Past Weather	- Flag
052	130	Pressure	- Flag
052	131	Dry-Bulb	- Flag
052	132	Wet-Bulb	- Flag
052	133	Dew Point	- Flag
052	134	Sea Temperature	- Flag
052	135	Clouds	- Flag
052	136	Waves	- Flag
052	137	Swells	- Flag
052	138	Pressure Change	- Flag
053	139-140	Quality Code	
054	140-142	QC - Year	
054	143-144	QC - Month	
055	145-148	Blank	

Flight Degradation Analysis Post-Processor
(Dietenberger, 1984)

Level Flight

Thrust Increase (%) to Maintain Level Flight in Icing

$$= 100\left[\frac{1+\frac{\Delta C_D}{C_{D_o}}}{1-\frac{\Delta C_L}{C_{L_o}}}\right]$$

Velocity Increase (%) to Maintain Level Flight in Icing

$$= 100\left[1-\frac{\Delta C_L}{C_{L_o}}\right]^{-\frac{1}{2}}$$

Approach

Thrust Increase (%) to Maintain Sink Rate in Icing

$$= 100\left[\frac{\sin\gamma_o\left[1-\frac{\Delta C_L}{C_{L_o}}\right]^{\frac{1}{2}}+\frac{\rho S V_o^2}{2}\left[C_{D_o}+\Delta C_D\right]\left[1-\frac{\Delta C_L}{C_{L_o}}\right]^{-1}}{W\sin\gamma_o+\frac{\rho S V_o^2}{2}C_{D_o}}\right]$$

Velocity Increase (%) to Maintain Sink Rate in Icing

$$= 100\left[1-\frac{\Delta C_L}{C_{L_o}}\right]^{-\frac{1}{2}}$$

Glide Slope (γ) in Icing

$$= \gamma_o\left[1-\frac{\Delta C_L}{C_{L_o}}\right]^{\frac{1}{2}}$$

$$\Delta C_D = [\,a(k/c)^{\frac{1}{7}} - b\,][\,1-(1-p)^r\,]$$

$$C_{D_o} = .0146 + 1.066\times 10^{-4}\,(\alpha+5.9)^2$$

$$\frac{\Delta C_L}{C_{L_o}} = \left[C_1 + (C_2 - C_3 p)\ln\left(\frac{Re_c\,(k/c)}{C_4}\right)\right][\,1-(1-p)^n\,]$$

$$\alpha = \left[1 + C_0\frac{\Delta C_L}{C_{L_o}}\left(\frac{\alpha_*}{\alpha_o}-1\right)\right]$$

$$Re_c = \frac{V\,c}{\nu}$$

$a, b, C_0, C_1, C_2, C_3, C_4, r, n$ are airfoil calibration constants
c = chord length
k = roughness element height
p = icing extent from airfoil trailing edge
S = wing area
V_o = airspeed of clean aircraft
W = weight of the aircraft
α_o = clean wing pitch angle
α_* = zero lift pitch angle
γ_o = clean wing glide slope angle
ρ = density of the air
ν = viscosity of air

Once the TDF1129 file was created, subsequent degradation analyses could be easily run for different aircraft characteristics; the new thrust increase and maximum exposure time information would simply replace the previous data. Mock-ups for output from MAST are shown in Figures 5-13 to 5-16 and Tables 5-4 to 5-7.

Table 5-4 NB: SYNTHETIC DATA

ATMOSPHERIC ENVIRONMENT SERVICE
CANADIAN CLIMATE CENTRE

SERVICE DE L'ENVIRONNEMENT ATMOSPHERIQUE
CENTRE CLIMATOLOGIQUE CANADIENNE

MARINE CLIMATOLOGICAL SUMMARIES
FREQUENCY DISTRIBUTION OF ICING

RESUMES CLIMATOLOGIQUES MARITIMES
DISTRIBUTION DE FREQUENCE DU GIVRAGE

LOCATION: CABOT STRAIT
LIEU: DETROIT CABOT

PERIOD: 1960 - 1979
PERIODE: 1960 A 1979

POTENTIAL FIXED-WING ICING (850 MB, RIME)

	NONE	LIGHT	MODERATE	HEAVY	SEVERE	NO. OF READINGS
	GIVRAGE D'AREONEF (850 MB, GIVRE)					
	NULLE	FAIBLE	MODEREE	FORTE	DANGER-EUSE	NMBRE DE LECTURES
JANUARY/JANVIER	60	17	8	11	0	96
FEBRUARY/FEVRIER	55	17	9	6	1	88
MARCH/MARS	63	11	4	2	0	80
APRIL/AVRIL	169	10	0	0	0	179
MAY/MAI	244	1	0	0	0	245
JUNE/JUIN	194	0	0	0	0	194
JULY/JUILLET	189	0	0	0	0	189
AUGUST/AOUT	209	0	0	0	0	209
SEPTEMBER/SEPTEMBRE	171	0	0	0	0	171
OCTOBER/OCTOBRE	164	0	0	0	0	164
NOVEMBER/NOVEMBRE	178	1	0	0	0	179
DECEMBER/DECEMBRE	92	10	3	1	0	106

POTENTIAL FIXED-WING ICING (850 MB, MIXED)

	NONE	LIGHT	MODERATE	HEAVY	SEVERE	NO. OF READINGS
	GIVRAGE D'AREONEF (850 MB, GIVRE/VERGLAS)					
	NULLE	FAIBLE	MODEREE	FORTE	DANGER-EUSE	NMBRE DE LECTURES
JANUARY/JANVIER	60	17	8	11	0	96
FEBRUARY/FEVRIER	55	17	9	6	1	88
MARCH/MARS	63	11	4	2	0	80
APRIL/AVRIL	169	10	0	0	0	179
MAY/MAI	244	1	0	0	0	245
JUNE/JUIN	194	0	0	0	0	194
JULY/JUILLET	189	0	0	0	0	189
AUGUST/AOUT	209	0	0	0	0	209
SEPTEMBER/SEPTEMBRE	171	0	0	0	0	171
OCTOBER/OCTOBRE	164	0	0	0	0	164
NOVEMBER/NOVEMBRE	178	1	0	0	0	179
DECEMBER/DECEMBRE	92	10	3	1	0	106

POTENTIAL FIXED-WING ICING (850 MB, GLAZE)

	NONE	LIGHT	MODERATE	HEAVY	SEVERE	NO. OF READINGS
	GIVRAGE D'AERONEF (850 MB, VERGLAS)					
	NULLE	FAIBLE	MODEREE	FORTE	DANGER-EUSE	NMBRE DE LECTURES
JANUARY/JANVIER	60	17	8	11	0	96
FEBRUARY/FEVRIER	55	17	9	6	1	88
MARCH/MARS	63	11	4	2	0	80
APRIL/AVRIL	169	10	0	0	0	179
MAY/MAI	244	1	0	0	0	245
JUNE/JUIN	194	0	0	0	0	194
JULY/JUILLET	189	0	0	0	0	189
AUGUST/AOUT	209	0	0	0	0	209
SEPTEMBER/SEPTEMBRE	171	0	0	0	0	171
OCTOBER/OCTOBRE	164	0	0	0	0	164
NOVEMBER/NOVEMBRE	178	1	0	0	0	179
DECEMBER/DECEMBRE	92	10	3	1	0	106

POTENTIAL FIXED-WING ICING (850 MB, ALL)

	NONE	LIGHT	MODERATE	HEAVY	SEVERE	NO. OF READINGS
	GIVRAGE D'AREONEF (850 MB, TOTAL)					
	NULLE	FAIBLE	MODEREE	FORTE	DANGER-EUSE	NMBRE DE LECTURES
JANUARY/JANVIER	180	51	24	33	0	288
FEBRUARY/FEVRIER	165	51	27	18	3	264
MARCH/MARS	189	33	12	6	0	240
APRIL/AVRIL	507	30	0	0	0	537
MAY/MAI	732	3	0	0	0	735
JUNE/JUIN	582	0	0	0	0	582
JULY/JUILLET	567	0	0	0	0	567
AUGUST/AOUT	627	0	0	0	0	627
SEPTEMBER/SEPTEMBRE	513	0	0	0	0	513
OCTOBER/OCTOBRE	492	0	0	0	0	492
NOVEMBER/NOVEMBRE	534	3	0	0	0	537
DECEMBER/DECEMBRE	276	30	9	3	0	318

ENVIRONMENT CANADA
ATMOSPHERIC ENVIRONMENT
CANADIAN CLIMATE CENTRE

FIXED-WING ICING
POTENTIAL
1960 TO 1979
850 mb - ALL TYPES

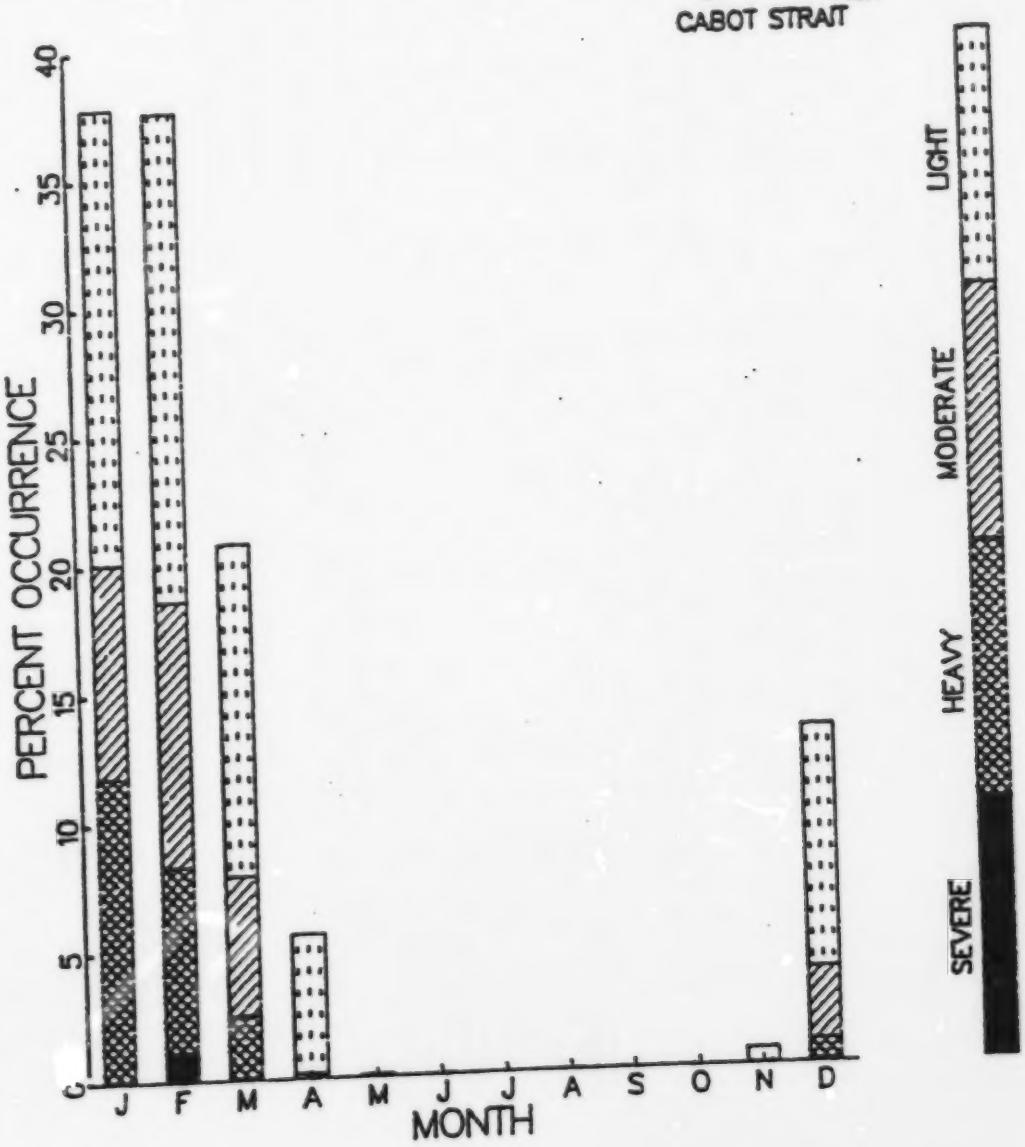


Figure 5-13 NB: SYNTHETIC DATA

Table 5-5 NB: SYNTHETIC DATA

ATMOSPHERIC ENVIRONMENT SERVICE
CANADIAN CLIMATE CENTRE

SERVICE DE L'ENVIRONNEMENT ATMOSPHERIQUE
CENTRE CLIMATOLOGIQUE CANADIENNE

MARINE CLIMATOLOGICAL SUMMARIES
FREQUENCY DISTRIBUTION OF ICING

RESUMES CLIMATOLOGIQUES MARITIMES
DISTRIBUTION DE FREQUENCE DU GIVRAGE

LOCATION: CABOT STRAIT
LIEU: DETROIT CABOT

PERIOD: 1960 - 1979
PERIODE: 1960 A 1979

POTENTIAL HELICOPTER ICING (850 MB)

GIVRAGE D'HELICOPTERE (850 MB)

	NONE / NULLE	RIME / GIVRE	MIXED / GIVRE/ VERGLAS	GLAZE / VERGLAS	NO. OF READINGS / NMBRE DE LECTURES
JANUARY/JANVIER	179	51	24	34	288
FEBRUARY/FEVRIER	164	50	27	19	260
MARCH/MARS	190	31	13	6	240
APRIL/AVRIL	506	29	1	0	536
MAY/MAI	733	1	0	0	734
JUNE/JUIN	581	0	0	0	581
JULY/JUILLET	566	0	0	0	566
AUGUST/AOUT	627	0	0	0	627
SEPTEMBER/SEPTEMBRE	512	0	0	0	512
OCTOBER/OCTOBRE	492	0	0	0	492
NOVEMBER/NOVEMBRE	533	3	0	0	536
DECEMBER/DECEMBRE	276	30	9	3	318

ENVIRONMENT CANADA
ATMOSPHERIC ENVIRONMENT

CANADIAN CLIMATE CENTRE

HELICOPTER ICING
POTENTIAL
1960 TO 1979
850 mb

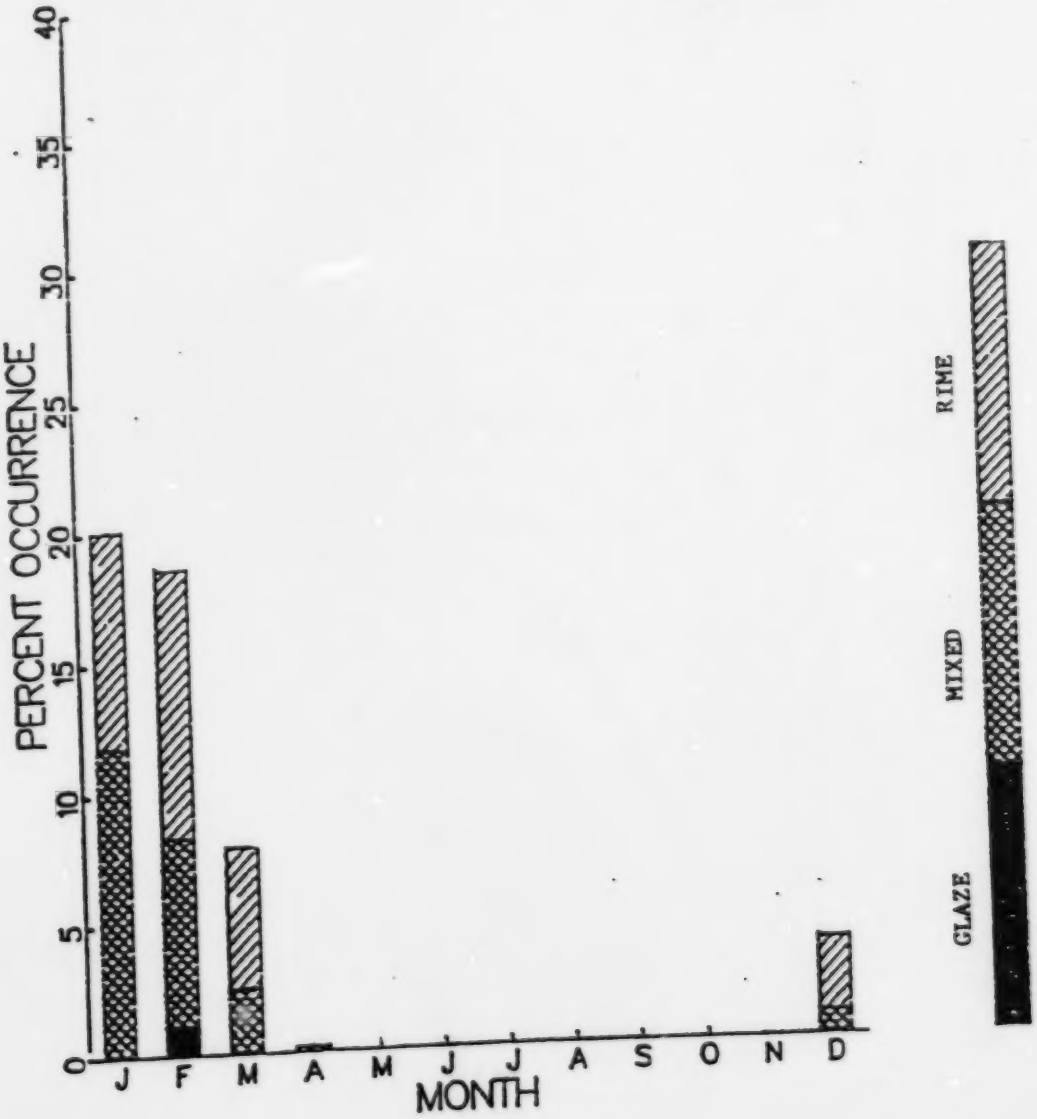


Figure 5-14 NB: SYNTHETIC DATA

Table 5-6 NB: SYNTHETIC DATA

ATMOSPHERIC ENVIRONMENT SERVICE
CANADIAN CLIMATE CENTRE

SERVICE DE L'ENVIRONNEMENT ATMOSPHERIQUE
CENTRE CLIMATOLOGIQUE CANADIENNE

MARINE CLIMATOLOGICAL SUMMARIES
FREQUENCY DISTRIBUTION OF FLIGHT
DEGRADATION DUE TO ICING

RESUMES CLIMATOLOGIQUES MARITIMES
DISTRIBUTION DE FREQUENCE .....

LOCATION: CABOT STRAIT
PERIOD: 1960 - 1979
LEVEL: 850 MB

LIEU: DETROIT CABOT
PERIODE: 1960 A 1979
LEVELE: 850 MB

POTENTIAL THRUST INCREASE ON APPROACH (GENERAL AVIATION)

	NONE	< 100 %	100-200 %	200-300 %	> 300 %	NO. OF READINGS
	NULLE	< 100 %	100-200 %	200-300 %	> 300 %	NMBRE DE LECTURES
JANUARY/JANVIER	179	51	24	34	0	288
FEBRUARY/FEVRIER	164	50	27	19	3	263
MARCH/MARS	190	31	13	6	0	240
APRIL/AVRIL	506	29	1	0	0	536
MAY/MAI	733	1	0	0	0	734
JUNE/JUIN	581	0	0	0	0	581
JULY/JUILLET	566	0	0	0	0	566
AUGUST/AOUT	627	0	0	0	0	627
SEPTEMBER/SEPTEMBRE	512	0	0	0	0	512
OCTOBER/OCTOBRE	492	0	0	0	0	492
NOVEMBER/NOVEMBRE	533	3	0	0	0	536
DECEMBER/DECEMBRE	276	30	9	3	0	318

ENVIRONMENT CANADA
ATMOSPHERIC ENVIRONMENT
CANADIAN CLIMATE CENTRE

POTENTIAL THRUST
INCREASE ON APPROACH
GENERAL AVIATION
1960 TO 1979
850 mb

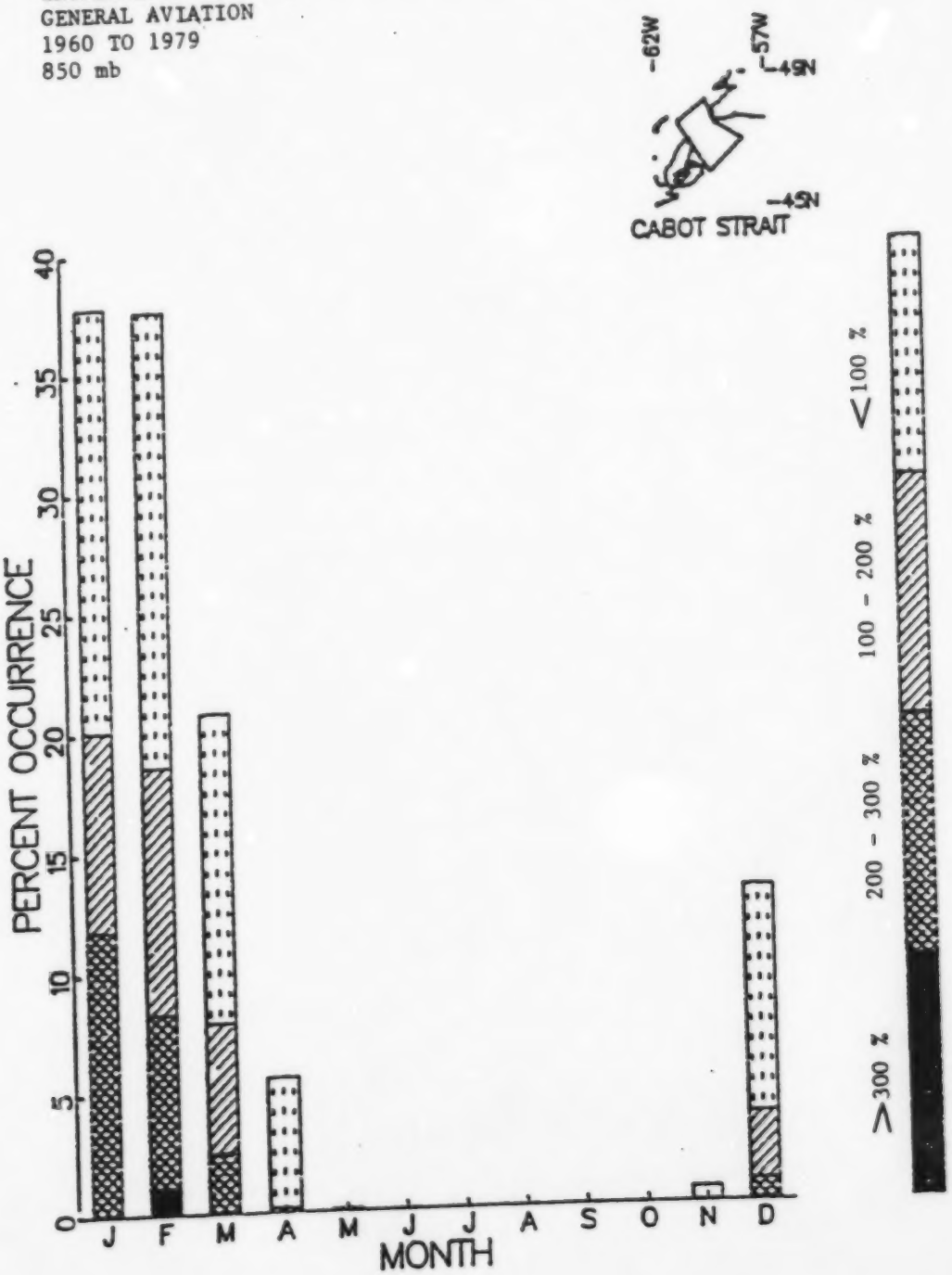


Figure 5-15 NB: SYNTHETIC DATA

Table 5-7 NB: SYNTHETIC DATA

ATMOSPHERIC ENVIRONMENT SERVICE
CANADIAN CLIMATE CENTRE

SERVICE DE L'ENVIRONNEMENT ATMOSPHERIQUE
CENTRE CLIMATOLOGIQUE CANADIENNE

MARINE CLIMATOLOGICAL SUMMARIES
FREQUENCY DISTRIBUTION OF FLIGHT
DEGRADATION DUE TO ICING

RESUMES CLIMATOLOGIQUES MARITIMES
DISTRIBUTION DE FREQUENCE .....

LOCATION: CABOT STRAIT
PERIOD: 1960 - 1979
LEVEL: 850 MB

LIEU: DETROIT CABOT
PERIODE: 1960 A 1979
LEVELE: 850 MB

MAXIMUM ICING EXPOSURE TIME (GENERAL AVIATION)

	NO ICE	> 60 MIN	30-60 MIN	10-30 MIN	< 10 MIN	NO. OF READINGS
	NULLE	> 60 MIN	30-60 MIN	10-30 MIN	< 10 MIN	NMBRE DE LECTURES
JANUARY/JANVIER	179	51	24	34	0	288
FEBRUARY/FEVRIER	164	50	27	19	3	263
MARCH/MARS	190	31	13	6	0	240
APRIL/AVRIL	506	29	1	0	0	536
MAY/MAI	733	1	0	0	0	734
JUNE/JUIN	581	0	0	0	0	581
JULY/JUILLET	566	0	0	0	0	566
AUGUST/AOUT	627	0	0	0	0	627
SEPTEMBER/SEPTEMBRE	512	0	0	0	0	512
OCTOBER/OCTOBRE	492	0	0	0	0	492
NOVEMBER/NOVEMBRE	533	3	0	0	0	536
DECEMBER/DECEMBRE	276	30	9	3	0	318

ENVIRONMENT CANADA
ATMOSPHERIC ENVIRONMENT
CANADIAN CLIMATE CENTRE

POTENTIAL MAXIMUM
ICING EXPOSURE TIME
1960 TO 1979
850 mb - GENERAL AVIATION

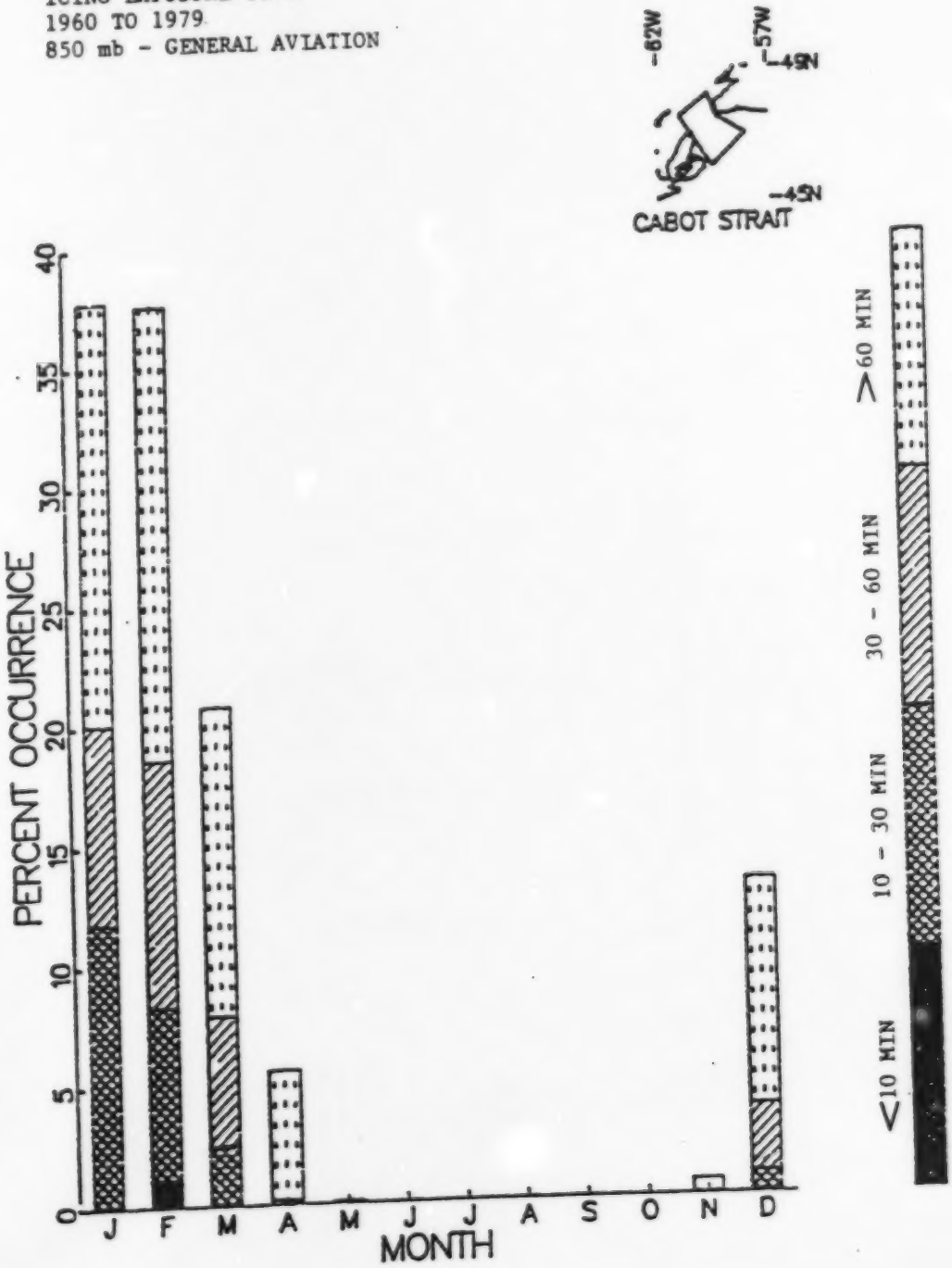


Figure 5-16 NB: SYNTHETIC DATA

6. CONCLUSIONS

This review has shown that limited climatological information exists concerning the extent of the (fixed-wing and rotary) aircraft icing hazard in Eastern Canadian airspace. However, the information available suggests that such a hazard does exist under fairly specific environmental conditions, and that the hazard to individual aircraft under identical environmental stress is highly variable.

The review of modelling techniques currently available has revealed several models that may be applied to the problem of the climatological assessment of aircraft icing within the limitations of available data and computer power. However, considerable evaluation and testing of these models will be required before they can be applied as a climatological analysis tool. A conceptual design of the model system has been presented, along with mock-ups of the potential model output to the user. Work required for the completion of a climatological prediction system for aircraft icing includes:

- establishment of an aviation icing and meteorological database for model evaluation;
- implementation of the candidate models;
- verification of the system with an independent data set.

To some extent, the achievement of the above goals may be problematical since the detail of available aviation icing data may not be sufficient for this purpose. To that end, it will be necessary that a thorough review of the data identified in Section 2 be conducted to determine the feasibility of the model development process.

REFERENCES

Ackerman, B., 1959: The Variability of the Water Contents of Tropical Cumuli: J. Meteor., 16, 191-198.

Ackerman, B., 1963: Some Observations of Water Contents in Hurricanes. J. Atmos. Sci., 20, 288-298.

Ackley, S.F. and M.K. Templeton, 1979: Computer Modeling of Atmospheric Ice Accretion. CRREL Report 79-4, 39 pp.

Ashley, H., 1945: Aircraft Icing Over Northwest Europe. AWSTR 105-46.

Air Weather Service, 1960: Forecasters Guide on Aircraft Icing. Manual Nr. 105-39, 51 pp.

Air Weather Service, 1980: Forecasters Guide on Aircraft Icing. AWS/TR-80/001, U.S. Air Force, Scott AFB.

Appleman, H.S., 1954: Design of a Cloud Phase Chart. Bull. Amer. Meteor. Soc., 35, 223-225.

Bain, M. and J.F. Gayet, 1982: Contribution to the Modeling of the Ice Accretion Process: Ice Density Variation with Impacted Surface Angle. First Intl. Workshop on Atmospheric Icing of Structures, L.D. Minsk (ed.), 1-3 June, 1982, Hanover, New Hampshire, CRREL Special Report 83-17, p. 13-20.

Bain, M., J.F., Gayet and R.G., Soulage, 1984: Ice Deposit Characteristics Versus Meteorological Parameters from Mountain Top Measurements and Comparisons with a Numerical Investigation. Proceedings of the 9th International Cloud Physics Conference, Tallinn, Estonian SSR,USSE 21-28 August 1984, 733-736.

Best, A.C., 1952: Occurrence of High Rates of Ice Accretion on Aircraft. Professional Notes of the Meteorological Office, London, 7, 22pp.

Bocchieri, J.R., 1980: The Objective Use of Upper Air Soundings to Specify Precipitation Type Mon. Wea. Rev., 108, 596-603.

Bowden, D.F., A.E. Gensemer and C.A. Skeer, 1963: Engineering Summary of Airframe Icing Technical Data. Flight Standards Service, FAA Tech. Rep. ADS-4.

Bragg, M.B., G.M. Gregorek and R.J. Shaw, 1981: An Analytical Approach to Airfoil Icing. AIAA Paper No. 81-0403.

Bragg, M.B. and G.M. Gregorek, 1982: Aerodynamic Characteristics of Airfoils with Ice Accretions. AIAA Paper 82-0282.

Bragg, M.B., 1984: Effect of Geometry on Airfoil Icing Characteristics. J. Aircraft, 21, 505-511.

Bragg, M.B., 1985: Predicting Rime Ice Accretion on Airfoils. AIAA Journal, 23, 381-387.

Brown, R. and S. Krishnasamy, 1984: Climatological Ice Accretion Modelling. Canadian Climate Centre Report No. 84-10, 195 pp.

Brown, R.D. and P. Roebber, 1985: The Scope of the Ice Accretion Problem in Canadian Waters Related to Offshore Energy and Transportation. Canadian Climate Centre Report 85-13, 295 pp.

Cansdale, J.T. and I.I. McNaughtan, 1977: Calculation of Surface Temperature and Ice Accretion Rate in a Mixed Water Droplet/Ice Crystal Cloud. Royal Aircraft Establishment, Technical Report 77090, 24 pp.

Chaine, P.M., 1974: In-Cloud Icing. Industrial Meteorology Study V, Atmospheric Environment Service, Environment Canada, Toronto.

Clark, V., 1948: Icing Nomenclature. Harvard-Mount Washington Icing Res. Report 1946-47. U.S.A.F. Tech. Rep. No. 5676, 415 pp.

Cohen, I.D., 1983: Analysis of AFGL Aircraft Icing Data, Report No. AFGL-TR-83-0170, Hanscom AFB, 45pp.

Cooper, W.A., W.R. Sand, M.K. Politovich and D.L. Veal, 1984: Effects of Icing on Performance of a Research Airplane. J. Aircraft, 21, 708-715.

Dietenberger, M.A., 1984: A Simple and Safe Takeoff on Landing Procedure with Wind Surface Contaminations. J. Aircraft, 21, 955-961.

Ervik, M. and S.M. Fikke, 1984: An Icing Model Applied on a Planned Transmission Line. Proceedings of the Second International Workshop on the Atmospheric Icing of Structures, 19-21 June 1984, Trondheim, Norway, 213-222.

Finstad, K.J., E.P. Lozowski and E.M. Gates, 1987: A Computational Investigation of Water Droplet Trajectories. Submitted to J. Atmos. Oceanic Technol.

Flemming, R.J. and D.A. Lednicer, 1986: Correlation of Icing Relationships with Airfoil and Rotorcraft Icing Data. J. Aircraft, 23, 737-743.

Gayet, J.F., M. Bain, and R.G. Soulage, 1984: Role of Ice Crystals on Ice Accretion Processes. Paper Presented at the Second Intl. Workshop on Atmospheric Icing of Structures, Trondheim, Norway, June 19-21, 1984.

Guttman, N.B. and R.K. Jeck, 1987: Aircraft Icing Environment in Low Ceiling Conditions near Washington, D.C. Weather and Forecasting, 2, 114-126.

Hoffmann, H.E., R. Roth and J. Demmel, 1986: Results of Icing Flight in Winter 1983/84: Dependence of Ice Accretion Thickness on Cloud-Physics Parameters As Well As Object and Cloud Parameters. European Space Agency Report ESA-TT-969, Technical Translation of DFVLR-FB-85-39, 40pp.

Hansman, R.J., 1985: Droplet Size Distribution Effects on Aircraft Ice Accretion. J. Aircraft, 22, 503-508.

Huffman, G.J. and G.A. Norman, 1985: Specifying Freezing Rain With Physically-Motivated Predictors. Proceedings of the Ninth Conference on Probability and Statistics in Atmospheric Sciences, 9-11 October, 1985, Virginia Beach, 487-493.

Huan, M., 1963: Izv. Akad. Nouk., SSSR, Ser. Geofiz, No. 2, 362.

Itagaki, K., 1984: Self-Shedding of Accreted Ice from High-Speed Rotors. Proceedings of Second International Workshop on Atmospheric Icing of Structures, 19-21 June 1984, Trondheim, Norway, p.95-100.

Jeck, R.K., 1986: Airborne Cloud-Physics Projects From 1974 through 1984. Bull. Amer. Meteor. Soc., 67, 1473-1477.

Jeck, R.K., 1985: An Assessment of Data Quality and Quantity From Airborne Cloud-Physics Projects From 1974 through 1984. Report No. DOT/FAA/CT-85/37, FAA Technical Center, Atlantic City Airport, N.J.

Jessup, R. Cr., 1984: Forecast Techniques for Ice Accretion on Different Types of Marine Structures, Including Ships, Platforms and Coastal Facilities (Draft Report). Atmospheric Environment Service, Downsview, Ontario, Canada, 89 pp.

Jensen, C.E., 1963: Prediction of Large-Scale Cloudiness and Airframe Icing Conditions by Machine Methods. J. Appl. Meteor., Vol. 2, p. 337-344.

Keeter, K.K. and R.P. Green, 1981: Forecasting the Predominance of Frozen Precipitation: An Alternative for the Classification of Mixed Precipitation Events and the Verification of Precipitation Type. National Weather Digest, 6, 17-20.

Kloner, M.O., 1970: Prediction of Ice Formations on an Airfoil. Lockhead Report No. W.O. 21-3760-3279, 28 pp.

Korkan, K.D., E.J. Cross and T.L. Miller, 1984: Performance Degradation of a Model Helicopter Rotor with a Generic Ice Shape. J. Aircraft, 21, 823-830.

Korkan, K.D., E.J. Cross and C.C. Cornell, 1985: Experimental Aerodynamic Characteristics of an NACA 0012 Airfoil with Simulated Ice. J. Aircraft, 22, 130-134.

Korkan, K.D., L. Dadone and R.J. Shaw, 1984a: Performance Degradation of Propeller Systems Due to Rime Ice Accretion. J. Aircraft, 21, 44-49.

Korkan, K.D., L. Dadone and R.J. Shaw, 1984b: Helicopter Rotor Performance Degradation in Natural Icing Encounter. J. Aircraft, 21, 84-85.

Lake, H.B. and J. Bradley, 1976: The Problem of Certifying Helicopters for Flight in Icing Conditions. Aeronautical Journal, October 1976, 419-433.

Langmuir, I. and K.B. Blodgett, 1946: Mathematical Investigations of Water Droplet Trajectories. G.E. Report RL-244. Reprinted in Colleted Works of I. Langmuir, Pergamon Press, p. 335-393.

Lawford, R.G., 1971: A Diagnostic Model for Computing Potential Airframe Icing. Technical Memoranda TEC 759, Dept. of the Environment, Atmospheric Environment Service, Toronto, Canada.

Le Sueur, H.E., 1978: Airworthness of Helicopters. Aeronautical Journal, October 1978.

Lewis, W., 1947: A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes. NACA TN 1393.

Lozowski, E.P. and M.M. Oleskiw, 1983: Computer Modeling of Time-Dependent Rime Icing in the Atmosphere. CRREL Report 83-2, 74 pp.

List, R., 1977: Ice Accretions on Structures. Journal of Glaciology, 19, 451-465.

Lozowski, E.P., Stallabrass, J.R. and P.F. Hearty, 1979: The Icing of an Unheated Non-Rotating Cylinder in Liquid Water Droplet - Ice Crystal Clouds. National Research Council Canada, Division of Mechanical Engineering, Laboratory Technical Report LTR-LT-96, 109 pp.

MacArthur, C.D., 1983: Numerical Simulation of Airfoil Ice Accretion. Paper Prepared for the 21st Aerospace Sciences Meeting, Reno, Nevada, AIAA-83-0112.

Macklin, W.C., 1962: The Density and Structure of Ice Formed by Accretion, Q.J.R.M.S., 88., p. 30-50.

Makkonen, L., 1984: Modeling of Ice Accretion on Wires. Journal of Clim. and Appl. Met., Vol. 23, No. 6, p. 929-939.

Makkonen, L. and J.R. Stallabrass, 1987: Experiments on the Cloud Droplet Collision Efficiency of Cylinders. J. Clim. and Appl. Meteor., 26, 1406-1411.

Mitten, P., P. Paschke and R.D. Brown, 1985: Atmospheric Icing on Oil Rigs off Canada's East Coast. Proc. Int'l Workshop on Offshore Winds and Icing, Halifax, Nova Scotia, October 7-11, 1985., p. 293-312.

Mortsch, L.D., T. Agnew, A. Saulesleja and V.R. Swail, 1985: Marine Climatological Atlas - Canadian East Coast. Canadian Climate Centre Report No. 85-11, 343 pp.

Newton, D.W., 1978: An Integrated Approach to the Problem of Aircraft Icing. J. Aircraft, 15, 374-380.

Perkins, P.J., W. Lewis, and D.R. Mulholland, 1957: Statistical Study of Aircraft Icing Probabilities at the 700- and 500-millibar Levels over Ocean Areas in the Northern Hemisphere. NACA Tech. Note 3984, NACA, May 1957.

Pruppacher, H.R. and J.D. Klett, 1980: Microphysics of Clouds and Precipitation. D. Reidel Publishing Company, Boston, U.S.A.

Roebber, P., and P. Mitten, 1987: Modelling and Measurement of Icing in Canadian Waters. Canadian Climate Centre Report 87-15, 150 pp.

Sand, W.R., W.A. Cooper, M.K. Politovich and D.L. Veal, 1984: Icing Conditions Encountered by a Research Aircraft. J. Clim. and Appl. Meteor., 23, 1427-1440.

Shaw, R.J., 1984: Progress Toward the Development of an Aircraft Icing Analysis Capability. NASA Tech. Memorandum 83562.

Skatski, V.I., 1965: Some Results from Experimental Study of the Liquid Water Content in Cumulus Clouds. In Atmos. Oceanic Phys., 1, 479-487.

Stallabrass, J.R. and R.D. Price, 1967: The Effect of Icing During Helicopter Ground Run-up. National Research Council Canada, Department of Mechanical Engineering, Test Report MET-491, 4 pp.

Swail, V.R. and L.D. Mortsch, 1984: A Review of the State-of-the-Art in Marine Climatology on the East Coast of Canada. Climatological Studies Report No. 36, 82 pp.

Sweeney, H.J. and I.D. Cohen, 1985: Some Microphysical Processes Affecting Aircraft Icing-Final Report. Report No. AFGL-TR-85-0100 ERT 914, Air Force Geophysics Laboratory, Hanscom AFB, 37 pp.

Thompson, J.K., 1955: 1954 Icing Presentation for Major Commands. WADC Tech. Note WCI 55-26 (AD-69347).

Toliver, R., 1987: Formation and Accretion of Supercooled Water Droplets and Their Effect on Aircraft. J. Env. Sciences, 30, 27-30.

Tucker, W.B., 1983: Current Procedures for Forecasting Aviation Icing. U.S. Army Cold Regions Research and Engineering Laboratory Report No. 83-24, Hanover, New Hampshire, 31 pp.

Voskresenskii, A.I. and K.I. Chukanin, 1959: The Meteorological Conditions of Icing in St. and Sc Clouds. Trudy, 228(1), p. 124-134. Translated for the U.S. Air Force Geophysics Research Directorate under contract number AF 19(604)-6113.

Wallace, J.M. and P.V. Hobbs, 1977: Atmospheric Science. An Introductory Survey. Academic Press, New York, 467 pp. Skatski, V.I., 1965: Some Results from Experimental Study of the Liquid Water Content in Cumulus Clouds. In Atmos. Oceanic Phys., 1, 479-487.

Warner, J., 1955: The Water Content of Cumuliform Cloud. Tellus, 7, 449-457.

Warner, J., 1969: The Microstructure of Cumulus Cloud. Part I. General Features of the Droplet Spectrum. J. Atmos. Sci., 26, 1049-1059.

Warner, J., 1970: On Steady-State One-Dimensional Models of Cumulus Convection. J. Atmos. Sci., 27, 1035-1040.